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AIRCRAFT MISHAP INVESTIGATION HANDBOOK FOR ELECTRONIC HARDWARE

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Executive Summary

This handbook contains procedures and guidelines to aid in the analysis and investigation of electrical and electronic components encountered during aircraft mishap investigations. This handbook is intended to be a reference manual for personnel involved in mishap investigations. The handbook has three parts.

Part I is an overview of electronic component failure analysis as it relates to aircraft mishap investigations. It covers the role of electrical and electronic equipment in aircraft mishaps and includes a summary of the analysis procedures which are covered in detail in Part II. The summary describes some of the analytical tools and procedures used, and the kinds of information that might be obtained from the analysis of each type of component. Part I provides a useful overview for those involved in the management of mishap investigations. It may also be useful for technical support personnel who need an introduction to electronic component analysis.

Part II of the handbook provides procedural guidelines for the examination of six different types of components found in aircraft. These include: lamps, wiring, connectors, circuit breakers, printed wiring boards, and microelectronic devices. Many of the analytical techniques presented here can be used on other components as well. Each chapter covers the construction of the component, its theory of operation, and failure characteristics which are important during component analysis. Numerous drawings, reference data, and photographs of damaged and undamaged components are included. The ability for certain components or analysis techniques to provide information about the aircraft prior to impact has been stressed in each chapter. Part II of the handbook will be useful for those performing field and laboratory analysis of the electronic components in support of the overall mishap investigation activity.

Part III of the handbook consists of two appendices. Appendix A is a bibliography list of over 170 references used in the development of the handbook. The bibliography list identifies numerous textbooks, papers, and government studies covering component construction, analysis procedures, and related engineering practice. Appendix B is a glossary of failure analysis terms.

PART I

INTRODUCTION AND BACKGROUND

Introduction Electrical equipment plays a unique role in aircraft mishap investigation. In the early days of aircraft, when mechanical components were the cause of many failures, the failed component itself provided most of the information about its own failure. Metallurgical analysis of a specific gear, bearing, or cable identified both the location and cause of the failure.

Electrical failures can be somewhat more evasive, however. The wire that shorts to the airframe on one side of the aircraft can easily induce related failures of equipment on the other side.

Much of mishap investigation is a process of elimination. Electrical components support the process by providing useful information about what parts of the aircraft were or were not working during the mishap.

Aircraft mishaps, both in the air and on the ground, are often the result of on-board fires. Heat or arcing from malfunctioning electrical equipment are frequently considered a possible source of ignition in these incidents. This is another reason that electrical components are important during mishap investigation.

There are three general reasons that electrical equipment is analyzed during mishap investigation. These are:

1. Electrical failure can play a causal role in mishaps.
2. Electrical equipment may provide information about the state of aircraft systems.
3. The equipment may have been a source of ignition for an on-board fire.

Contents

This part of the handbook is organized into the following sections.

Section	Topic	See Page
A	Causes of Aircraft Electrical Failures	3
B	The Electric Power System of an Aircraft	7
C	Summary of Key Failure Analysis Tools	9
D	Overview of Component Analysis Techniques	15

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SECTION A

CAUSES OF AIRCRAFT ELECTRICAL FAILURES

OVERVIEW

Introduction Data on electronic component failures provides some insight into the kinds of components that can cause aircraft mishaps. Data was examined from three independent sources to identify electrical components which fail frequently on aircraft:

1. A survey of mishap data from the Air Force Safety Center.
2. A paper describing a study based on data from the Air Force Avionics Integrity Program (AVIP).
3. Data published by Hughes Aircraft.

Mishap Data The Air Force Safety Center maintains a database of aircraft mishap reports for all aircraft in service in the U.S. Air Force. In general, mishap reports are filed for any condition which affects the safety of the aircraft. The reports include a description of the mishap, condition of the aircraft and the type of component which appears to be responsible. Mishap reports in which an electrical or electronic component were identified were reviewed covering the three year period 1986-1989. The results are summarized in Figure 1. A more detailed discussion of the analysis is presented in [1].

AVIP A paper describing the Avionics Integrity Program (AVIP) [2] includes a summary of electrical failure causes on aircraft. The data is shown in Figure 2. The paper suggests that connectors account for about 40% of maintenance repairs on aircraft electrical equipment. The formation of surface films that cause connectors to be non-conductive is identified as a major problem. Interconnections on circuit boards (including traces, plated-through-holes, and sockets) and electronic components on circuit boards are also identified as major contributors to failure.

Hughes Aircraft A study conducted by Hughes Aircraft on component failures on PWBs is described in [3]. The study includes data on four types of PWBs of different ages and complexity levels. The results are based on part replacement data from factory test and quality control activities, not field failures. The results of the study are shown in Figure 3.

Continued on next page

OVERVIEW, Continued

Conclusions

1. A large percentage of aircraft mishaps involving electronics are caused by faulty interconnections. Wiring and connectors are included in this category.
2. Contamination is the primary cause of connector failures.
3. Chafing is a major cause of wiring failures.
4. Connector and semiconductor failures are major problems on printed wiring boards.

EXAMPLES

Figure 1

Figure 1. Aircraft Mishap Causes
Norton AFB Data [1]

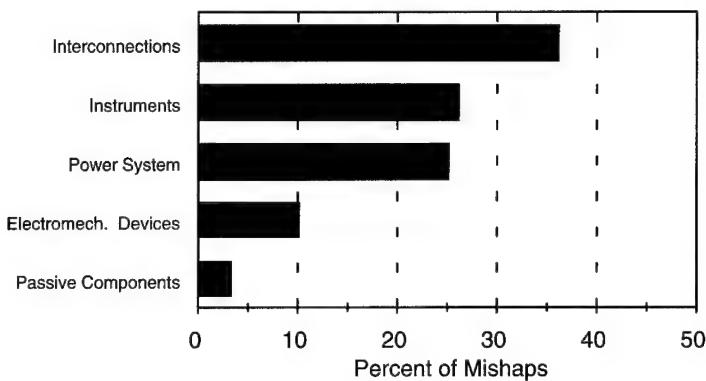


Figure 2

Figure 2. Aircraft Equipment Failures
Avionics Integrity Program Data [2]

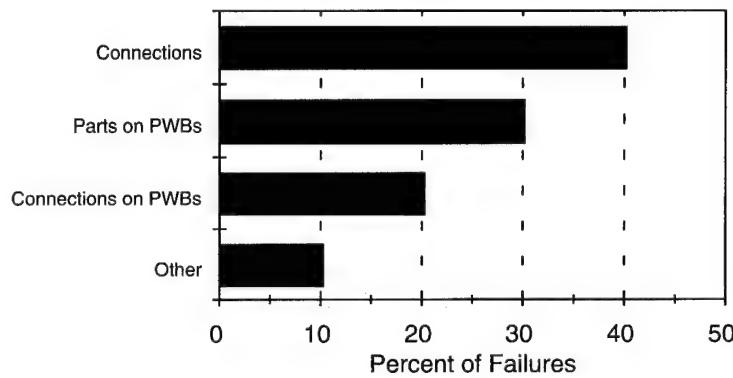
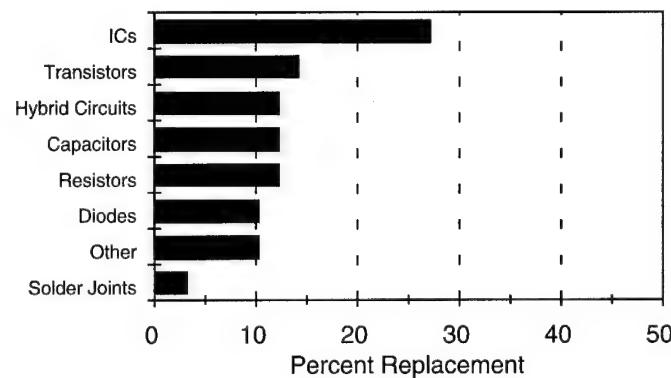


Figure 3

Figure 3. PWB Replacement Data
Hughes Aircraft [3]



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SECTION B

THE ELECTRIC POWER SYSTEM OF AN AIRCRAFT

OVERVIEW

Introduction The field mishap investigator should have a general knowledge of aircraft electrical systems. These systems depend on the size, type and age of the aircraft. There are, however, common characteristics which are covered in the discussions below [4].

Types of Power There are three basic types of power used on military aircraft. These are:

1. 120/208 3 phase power at 400 Hz from engine-driven generators. The system provides 120 line-to-neutral voltage for single phase loads and 208 Volts line-to-line for three phase loads. The neutral is grounded to the airframe for short circuit detection and protection.
2. 28 Vdc is provided by storage batteries, which are usually of the conventional lead-acid variety. They are used for engine starting, instrument illumination, motors and actuators, and other applications. They are especially useful for high current applications.
3. 270 Vdc is provided for modern equipment which operates directly at the higher voltage. 270 Vdc distribution has the advantage that it requires less volume and weight of the conductor for the same end-use device power ratings. Most electronic equipment converts the 270 V to lower voltages internally.

Power System Ratings Power system ratings are usually described in terms of the kVA rating of the onboard generators. Most aircraft are equipped with at least two identical systems, each of which can supply enough power for the entire aircraft. Two engine aircraft usually have one generator on each engine as a minimum. Some aircraft will also have an auxiliary power unit (APU) which is powered by a smaller engine that is not used for propulsion.

Total power system ratings for small aircraft are on the order of 50 kVA while larger aircraft can have ratings of 250 kVA and higher. Modern aircraft tend to have higher electric power loads because of their increasing dependence on electric accessories and onboard electronics and computers.

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OVERVIEW, Continued

Battery Circuits

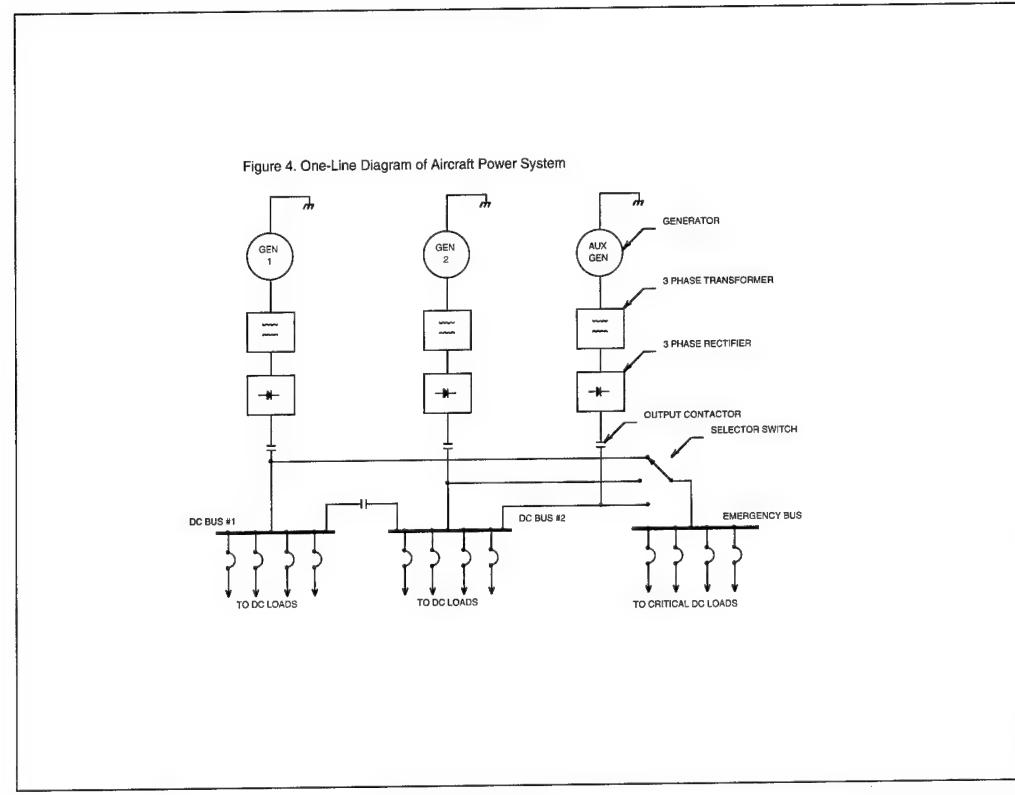
Battery systems usually use lead acid batteries. These batteries tend to develop very high short circuit currents. This can cause melting and arcing of conductors if the short circuit occurs close enough to the battery terminals. Currents in excess of 1000A can be generated for periods up to several seconds, depending on the wiring and type of battery. Battery circuits should be examined carefully during any electrical system investigation, especially if electrical ignition sources are suspected.

System Diagram

The simplified schematic for a hypothetical aircraft power system is shown in Figure 4. The diagram is called a “one-line diagram” since the three phases are represented by just one line on the diagram. The system has two main generators and an auxiliary generator. Power delivery is at 28 Vdc using two main buses and one emergency bus. Either of the two main generators can supply all the dc loads on the aircraft. By opening and closing the appropriate contactors any of the generators can supply the loads. The contactors are also used to disconnect a generator circuit when a failure is detected so that power from one generator does not flow back into one of the others.

In emergency conditions the auxiliary generator is connected to the loads. A selector switch is provided for a separate emergency bus which provides power to critical loads.

Figure 4



SECTION C

SUMMARY OF KEY FAILURE ANALYSIS TOOLS

OVERVIEW

Introduction A wide variety of analysis tools and techniques are available to the mishap investigator and laboratory analyst for examining electrical and electronic components. Four of the most common tools are discussed here to provide a general background and introduction. These are:

- Optical Microscopy
- Scanning Electron Microscopy
- X-ray Radiography
- Electrical Measurements

OPTICAL MICROSCOPY

Introduction Several types of optical microscopes are available to the failure analyst. Each type has a range of benefits and applications suited to particular type of examination.

Laboratory Camera The laboratory camera is a high quality camera mounted on an adjustable stand. It is designed for general purpose laboratory work and can accommodate objects from several feet to a fraction of an inch in size. The cameras usually use a medium format film such as a 4x5 inch size instead of 35 mm. They are useful for initial photography and documentation. Magnification is achieved with macro lenses and extension accessories which are mounted in the basic optical system of the camera. Magnifications up to about 15 times can be obtained, depending on the accessories used.

Stereo Microscope The stereo microscope (also called a stereoscope) is generally a low power, wide field microscope with a long working distance. It uses a binocular eyepiece and objectives to present a stereo image with good depth information. Magnifications from 5 to about 50 are typical. Stereoscopes are particularly useful for the initial examination of components, because they make it possible to see three dimensional aspects of the sample.

Metallurgical Microscope Metallurgical microscopes (also called metallographs) are the most common ones available to the failure analyst [5]. The metallograph is usually used to take microphotographs at precise magnifications for measurement purposes. The metallograph is a precision instrument used for examination of grain structure, fractures and other details of metallurgical materials. Magnifications from 10 to about 2000 are typical. Metallurgical microscopes have extremely limited depth of field. As a consequence, they are most useful when the sample can be mounted and ground flat and polished.

There are several types of illumination used with most metallographs. Two of the most common are:

Bright Field. The light source is directed through the microscope lens system so that the light is perpendicular to the surface of the sample. Most of the light is reflected back toward the microscope. This is the most commonly used type of illumination for metallography.

Dark Field. The light source is at an acute angle to the sample so that surface irregularities become illuminated prominently. Most of the light is reflected away from the microscope.

SCANNING ELECTRON MICROSCOPY

Introduction In a scanning electron microscope (SEM) the sample is placed in a vacuum chamber and subjected to an electron beam. The beam is electronically scanned over a region of the sample's surface and several forms of radiation are produced by the electrons striking the sample. The primary method for producing an image is by detecting secondary electrons generated by the scanned beam. The secondary electron detection signal creates an image on a cathode ray tube which is scanned in synchronism with the main beam [6].

The SEM has several advantages over the optical microscope. First, magnifications of at least 200,000 times are obtainable with higher attendant resolution than would be possible with light optics. Second, the depth of field is much greater than that for optical microscopes. Finally, elemental information can be obtained if the SEM is equipped with suitable accessories.

Elemental Information In addition to secondary electrons, two other forms of radiation produced by the electron beam can be used to provide information about the sample. These are backscattered electrons and X-rays. The backscattered electron signal produces an image in which the intensity is roughly proportional to the atomic number (z) of the element on the surface of the sample. This is called a backscattered electron (BSE) image.

X-ray radiation can be detected either by wavelength or energy content and used to identify the elements in the area of the sample being scanned. Elemental data from X-ray radiation are usually presented in a spectral graph. The two detection schemes are referred to as wavelength dispersive spectroscopy (WDS) and energy dispersive spectroscopy (EDS). EDS systems are more common and we only use that acronym throughout the handbook even though WDS is equally capable of the required detection.

Special Applications Two special applications of SEM examination are used for investigating failures of microelectronic devices.

In *voltage contrast imaging* a microelectronic device is energized while in the SEM vacuum chamber. Voltages present on the surface of the device modulate the secondary emission signal and hence the intensity of the image. The intensity variations are helpful in locating broken connections and other problems. The technique works with ac or dc voltages applied to the device. When low frequency ac voltages are used a striped pattern is produced on the image from the interference between the applied frequency and the beam sweep rate. This is called *stroboscopic voltage contrast* and is useful in obtaining timing information from the circuitry of the sample.

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SCANNING ELECTRON MICROSCOPY, Continued

Special Applications (Cont'd)

Electron beam induced current (EBIC) is an imaging technique in which the electron beam alters the conducting characteristics of semiconductor junctions in the device being examined. A small current is developed when the beam strikes the junction. An external amplifier uses the current to modulate the SEM image intensity. Beam voltage determines the penetration into the material and may be used to gauge junction depth.

X-RAY RADIOGRAPHY

Introduction X-ray radiography is useful for the initial examination of enclosed components, such as circuit breakers and connectors, to verify their initial condition before any significant testing is done. It also useful for examining wire bundles, equipment in metal enclosures and damaged assemblies.

Conventional X-Ray Conventional X-ray radiographs are produced by placing the object to be examined between a sheet of X-ray sensitive film and an X-ray source. Markers and calibrated samples of known X-ray density can be placed in the image area for documentation and to check for proper exposure. The film produces a negative image so that material of higher density (greater opacity to X-rays) appears lighter than that of lower density. The image on the film is usually the same size as the object as there is no inherent magnification.

Microfocus X-Ray This is a more advanced x-ray technique and is sometimes called real-time microfocus X-ray [7]. The technique differs from conventional X-ray methods in two ways. First, a special type of X-ray source is used which allows very high image resolution and magnifications up to about 200 times. Second, a special video camera arrangement is used instead of radiographic film, so that the X-ray image can be viewed in real time. Some equipment provides a means for manipulating the object while the X-ray image is viewed. This feature and the magnification are very useful, if not essential, in some investigations.

ELECTRICAL MEASUREMENTS

Introduction Measurement of the primary electrical quantities, voltage, current, and resistance, can be made both in the field and in the laboratory to aid in mishap investigation [8].

Field Measurements Practically any electrical measurement apparatus needed can be brought to the mishap site. For practical reasons field measurements are usually used for documenting the condition of components before removing them from the aircraft. A common example would be verifying the open or closed state of circuit breaker contacts and verifying that they agree with the button position. Most field measurements may be adequately made with a portable digital multimeter.

Laboratory Measurements Although any electrical measurement can come into play in mishap investigation resistance measurements are very common and fundamental to many electrical component failure modes. Two types of resistance measurements are described briefly below.

Insulation resistance is the resistance value of an insulating material intended to prevent electric current from flowing between electrically energized surfaces. A typical example is the insulation between pins on a connector where resistances above $100M\Omega$ are expected. Insulation resistance is usually measured by applying a high voltage across the insulating materials and then measuring the resulting current. The voltage can range from several volts to several thousand volts ac or dc, depending on the application. Insulation resistance degradation can be caused by contamination, thermal exposure, mechanical abrasion and other problems. Proper insulation resistance values are specified in the standards covering the component or equipment.

Contact resistance is the resistance value of mating metal parts intended to support the flow of electric current. A typical example is the resistance between closed circuit breaker contacts where values below 1Ω are expected. Contact resistance can be measured with conventional resistance meters or special meters designed to measure resistances in the $\mu\Omega$ range for critical applications. Proper contact resistance values are specified in the standards covering the component or equipment.

Voltage and current measurements can be made using the appropriate meters and will usually come into play when a failure mode is being recreated by constructing portions of an operating circuit or piece of equipment.

SECTION D

OVERVIEW OF COMPONENT ANALYSIS TECHNIQUES

OVERVIEW

Introduction The investigative techniques and the potential information which they can provide are covered briefly in the following articles. They cover the six fundamental component types included in Part II of the Handbook. These are:

- indicator lamps
- wiring
- circuit breakers
- connectors
- printed wiring boards
- microelectronics

INDICATOR LAMPS

Introduction A permanent deformation of the filament can occur when an energized incandescent lamp undergoes a severe impact. The deformation does not occur if the lamp is OFF. Examination of the filament after a mishap allows investigators to determine whether the lamp was ON or OFF at the time of impact [9].

Depending on the size of the lamp, impacts over several hundred G's may be needed before filament deformation occurs. These levels are the impact levels seen by the instrument panel or lamp cluster, not those associated with the usual calculated deceleration rate of the aircraft as it impacts the ground.

Indicator lamps are of interest during mishap investigation because they can provide information about the aircraft at the time of impact.

Types Indicator lamps for aircraft applications have a common structure. They all use a tungsten wire filament in an evacuated glass envelope. Sizes and ratings vary, but two of the most common lamps are the types 327 and 6839, which are used as indicators on instrument panels. Both lamps are less than 1/2 inch long and operate on 28 Vdc.

Analysis The basic mechanism relies on the fact that tungsten filament wires have higher ductility at the operating temperature than they do when they are cold. This allows filament deformation to occur when the filament is hot and the deformation is usually an indication that the lamp was ON at impact. The technique can provide reliable information about whether the lamp was ON or OFF at impact, especially if several lamps from the same panel can be examined.

The deformation can be seen in the field in some cases with a magnifying glass at 10X for preliminary assessments. Low power optical microscopy is the customary tool for most laboratory analysis. In some cases the fracture surface of broken filaments need to be examined in the SEM.

It is useful to identify some lamps which were ON at impact and submit them for laboratory analysis. This gives the laboratory analysts a convenient point of reference for comparison with other lamps and verifies that the G levels were high enough for filament deformation to be meaningful.

WIRING

Introduction

Modern military aircraft contain a tremendous amount of electric wiring. One estimate suggests that a typical fighter contains 10-15 miles of wire. Although these numbers change, depending on the technology and age of the aircraft, it seems clear that wiring will always be a part of the aircraft structure and frequently becomes of interest during mishap investigation.

Aircraft wiring is of interest during an investigation for three reasons.

- wiring failures can cause key aircraft systems to fail or misoperate.
- arcing and sparks from wiring failures are a potential fire ignition source.
- the condition of the wiring may indicate the state of key aircraft systems.

Types

Aircraft wiring is almost all stranded copper wire coated with one of three plating materials: tin, nickel, or silver - with silver being the most common. The copper strands are made of two alloys: OFHC (oxygen-free high conductivity) or HSCA (high strength copper alloy). All wire is covered with an insulation material: most are polymeric. There are several polymeric insulations presently in use in aircraft [10]. One of the most common is a polyimide tape-wound insulation used on wiring meeting the requirements of MIL-W-81381.

Analysis

Massive arcing damage in wire bundles is always of interest. These usually involve a number of conductors in a bundle which arc to a structural member at some point. Certain types of arcing conditions can be verified by elemental analysis in the SEM. When arcing takes place between two different materials, they may be transferred across the arcing region. Elemental analysis can verify the presence of aluminum in melted copper, for example, or copper deposited on an aluminum structural member.

Chafing and abrasion of insulation materials are usually caused by some type of fastener, equipment, or structural member rubbing directly against the wire. Since the damage is usually too severe to find the original source, aircraft similar to the one in question may need to be examined to find the precursor conditions.

The insulating materials used on aircraft wire are selected to withstand high operating temperatures. As a result, the wire insulation can show evidence of a localized heat source. Also, short time electrical events can cause substantial heating in the conductor before the exterior of the insulation is damaged. Microscopic examination of the interior and exterior insulation surfaces can sometimes reveal useful information.

Continued on next page

WIRING, Continued

Analysis (Cont'd) Melting of copper wire occasionally occurs from post-impact fire damage. This can usually be distinguished from melting caused by arcing because arcing is more localized and generates higher local temperatures. A key visual indicator is that arcing usually produces ball-like formations on the wire at the point of arcing. Optical microscopy is useful to help identify these characteristics.

CIRCUIT BREAKERS

Introduction Aircraft circuit breakers are the primary means of manually energizing equipment and provide overcurrent protection in case a short circuit or major equipment failure occurs. The button is the operating means for switching and also moves to the OFF position during an overcurrent trip. Therefore, the button position indicates whether a circuit was energized prior to impact.

Circuit breakers are of interest during mishap investigation for two main reasons.

- the handle indicates which aircraft systems were ON during the mishap.
- the condition of the contacts provides information about the connected electrical loads.

Types Most aircraft circuit breakers use a thermal trip mechanism to accomplish the overcurrent detection function. They have a button which indicates the open or closed state of the circuit breaker [11]. They are rated for operation on ac and dc supplies and meet the requirements of MIL-C-5809.

Analysis Circuit breaker malfunctions can occur in which the position of the button does not indicate the state of the contacts. These conditions are somewhat unstable and therefore it is critical not to manipulate the circuit breaker prior to laboratory analysis. One of the first steps in the analysis is to prepare an X-ray radiograph of the breaker to verify that the button position is consistent with the state of the contacts.

Microscopic examination of the circuit breaker contacts may provide some information about the history of the device. This examination is somewhat more useful on breakers from dc circuits than those on ac circuits. Material is transferred between contacts of dc circuit breakers in the direction of current flow (from positive to negative). Sometimes this can be useful in verifying a breaker's operation and loading condition. Also, short-time high current overload conditions will tend to leave an appearance of the contacts which is different than normal operation.

Measurements of the contact resistance and leakage resistance between the contacts and the case are also useful for evaluating circuit breakers. Contact resistance values are usually below 0.1Ω while leakage resistance values are normally above $1M\Omega$. Abnormal values indicate potential failure modes.

CONNECTORS

Introduction Connector failures result from several factors. Among these are corrosion from environmental contamination, electrical breakdown of the insulation materials, and mechanical failure due to problems in installation, repairs, and location.

Types Aircraft connectors come in a variety of styles, mechanical configurations, and contact materials. Connectors interconnecting equipment and wiring harnesses are almost all cylindrical in external appearance. Cylindrical connectors use a pin and socket contact arrangement with the pins arranged in a series of circular rows or a simple geometric variation [12]. One of the widely used circular connector configurations is based on MIL-C-38999.

Pieces of equipment are sometimes fitted with connectors which mate with a rack in the airframe. These are called rack and panel connectors. Most use pins, but the overall shape is not cylindrical. Printed wiring boards use different styles of connectors which may consist of pins, or flexing strips that lay against the plated traces on the board.

The contacts of most aircraft connectors are gold plated to reduce contact resistance and protect against corrosion. Base materials in pins are copper and copper alloys, depending on the connector type.

Analysis Contamination and mechanical deterioration are leading causes of connector failures. The failures usually lead to one of two electrical problems:

- (1) abnormally high resistance in the connections between the mating parts of the connectors and,
- (2) abnormally low resistance between pins which are normally insulated from one another.

When significant power is available in the circuit, either of these problems can lead to overheating in the connector, due to the thermal product of the voltage-times-current.

The principal tools for investigating connector failures are electrical measurement, and SEM/EDS for identifying contaminants. Metallurgical analysis of connector parts is sometimes conducted to examine plating conditions and problems.

PRINTED WIRING BOARDS

Introduction The printed wiring board (PWB) is one of the most complex types of hardware that the electrical failure analyst will encounter during mishap investigation. The simplest PWB has a substrate made of a glass-epoxy composite with copper clad circuit traces. The manufacturing of the assembly involves more than a dozen chemical and material processing steps. These include photographic processes, electroplating, chemical etching, drilling, component insertion and soldering [13].

The complexity and range of materials gives rise to a number of failure modes, but also provides the opportunity to obtain additional pre-impact information. For example, the melting point of solder is 183°C while that of copper is 1083°C. This means that copper circuit traces that melted during a pre-impact electrical failure will probably survive some exposure to post impact fire. Solder, on the other hand, will be a better indicator of general thermal exposure.

Types A wide variety of PWB types are found on aircraft. They are classified by several factors.

1. Number of sides. This indicates how many layers or surfaces include copper circuit traces. The usual types are single-sided, double-sided and multilayer.
2. Component mounting. PWBs can have surface mount or through-hole construction. Some PWBs have a combination of both methods.
3. Flexible or rigid. Flexible circuits have a thin plastic substrate and copper clad circuit traces. They are used where the circuit must take on an unusual shape or has some flexing requirements. Conventional PWB construction uses a rigid substrate. Some circuits use rigid-flex construction where rigid circuit boards are interconnected with flexible ribbons carrying the necessary conductors.

Analysis Since electronic components are easily damaged by impact and fire exposure, it is unusual to find a PWB that has survived to the extent that electrical failures can be identified by direct testing. As a result, comparative testing is usually required to confirm the failure mechanism.

Impact damage is a good general indicator and can be examined by simple visual inspection. Displacement of melted solder can indicate melting as a result of elevated temperatures from an in-flight fire.

Continued on next page

PRINTED WIRING BOARDS, Continued

Analysis (Cont'd) Thermal damage can provide several indications, depending on the specific conditions. Localized damage may indicate some type of electrical failure. General damage, melting, and discoloration of the substrate are typical indicators of exposure to post-impact fire. Visual examination and low power optical microscopy are the best tools for analysis.

MICROELECTRONICS

Introduction Microelectronic devices are found in all areas of modern military aircraft. They control engines, weapons, communications equipment, and flight controls. The proliferation of microelectronic devices has ushered in a new era of military and commercial aircraft in which the conventional mechanical cockpit instruments have been replaced with electronic displays. This has been called the “glass cockpit” effect and has forced mishap investigators to probe into the microelectronic devices which are operating behind the scenes to control the aircraft.

In addition to their potential for playing a causal role in a mishap, microelectronic devices have become increasingly important for their role in storing critical flight data. A special class of microelectronic memory circuits retains memory even after power is removed from the equipment. These are called non-volatile memory circuits and are used on modern aircraft to store engine and communication system parameters, and record the status of on-board systems.

Types Microelectronic devices include discrete semiconductors, such as diodes and transistors, and integrated circuits. Integrated circuits (ICs) are distinguished by several factors including package type, fabrication technology, integration level, and device function. Military IC packages can be made of plastic, ceramic, or metal. The package types range from simple 14 pin dual-inline-package (DIP) or hybrid IC devices in metal can packages [14].

There are several key parts to an IC which are useful to understand when considering laboratory analysis.

- Package: Plastic, ceramic or metal package which protects the IC itself.
- Die: The IC which is mounted inside the package.
- Lead Frame: A series of formed metal leads for mounting, and connections which are external to the package.
- Wire Bonds: Small wire leads from the inside ends of the lead frame to the electrical connections on the surface of the die.

Continued on next page

MICROELECTRONICS, Continued

Analysis

Microelectronic devices will seldom survive impact and fire damage well enough to provide useful information by direct examination. However, when the damage is not too severe some evidence of pre-impact conditions may be preserved. Comparative testing will, of course, always be an alternative. For the most part the analysis will need to be conducted with the SEM and will require that the devices undergo a critical package removal process before-hand.

Overvoltage conditions can be caused by failures of surrounding circuitry or other causes. Physical damage to the device can sometimes be associated with specific types of overvoltage failure modes.

Overcurrent conditions in a given device can be caused by failures of attached circuits. They can lead to a catastrophic failure of the device leads inside the package or of the metallization traces on the IC die itself. Melting of the leads or traces is usually the key indicator.

Although most packages are sealed in dry nitrogen some are not. In the case of the latter, corrosion can be caused by contamination that enters the package during manufacture, or by package failures that allow air and moisture to enter the package while the device is in operation.

Wire bond failures are caused by mechanical stress, vibration, and bond abnormalities that can occur during manufacturing. Cracking at the wire lead bond to the IC surface can cause intermittent or broken electrical connections.

Impact damage usually causes severe cracking and separation of the IC die from the package.

Thermal damage causes melting of the materials used in the microelectronic device. The melting points may cover a wide temperature range. Useful information can sometimes be obtained, depending on the failure mode of the device and the thermal exposure it received during the mishap.

Altered electrical characteristics can be caused by contamination, electrical stress, or thermal exposure. Electrical characteristics can be checked on simple devices using a test instrument called a curve tracer. More complex devices are tested on an IC tester. It is relatively uncommon for this type of testing to be useful unless sufficient correlation exists between sample devices and those involved in the mishap.

Continued on next page

MICROELECTRONICS, Continued

**Non-volatile
Memory
Devices**

Non-volatile memory (NVM) devices store information after circuit power is removed, and are therefore of great interest in mishap investigation. They are used to store engine and communication system parameters and record the status of on-board systems. In some cases this data has been recovered and used to help determine the cause of a mishap.

The equipment containing NVM should be identified as soon as possible and sent to a qualified laboratory for analysis. It is critically important not to apply power to this equipment during handling, since some of the equipment may be faulty and cause memory contents to be lost if improperly energized.

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CHAPTER 1

LAMPS

OVERVIEW

Introduction The examination of incandescent filament lamps is one of the classical areas of aircraft accident investigation [1.1 - 1.3]. The fundamental physical mechanism that allows the condition of the lamp to be determined is filament deformation. At the high operating temperature of incandescent lamps the filament becomes relatively ductile and will permanently deform upon impact. If the lamp is OFF it is less likely to deform, but may fracture in a brittle fashion.

Knowledge about the status of aircraft lamps at the time of impact can give the investigator important clues about the condition of the aircraft just prior to impact.

For panel indicator and warning lamps the state (ON or OFF) of the lamp provides information about the status of systems, controls, and engines.

Other types of lamps can provide information about specific activities and systems, too. Some of these are found in landing lights, instrument illumination lights, and lighting for utility functions.

There are several different types of electric lights and displays found on modern aircraft. These include fluorescent lamps, electronic flash lamps, light-emitting diodes and cathode ray tube displays. As far as is known today, only incandescent lamps can give relatively definitive information about their state at the time of impact. Therefore, this chapter deals only with incandescent lamps.

Contents

This chapter is divided into four sections.

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B	Failure Characteristics	41
C	Failure Analysis Procedures	59
D	References	69

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SECTION A

BACKGROUND

OVERVIEW

Introduction This section provides the investigator with background information on the construction and operation of incandescent lamps used for aircraft applications.

Contents This section includes the following topics.

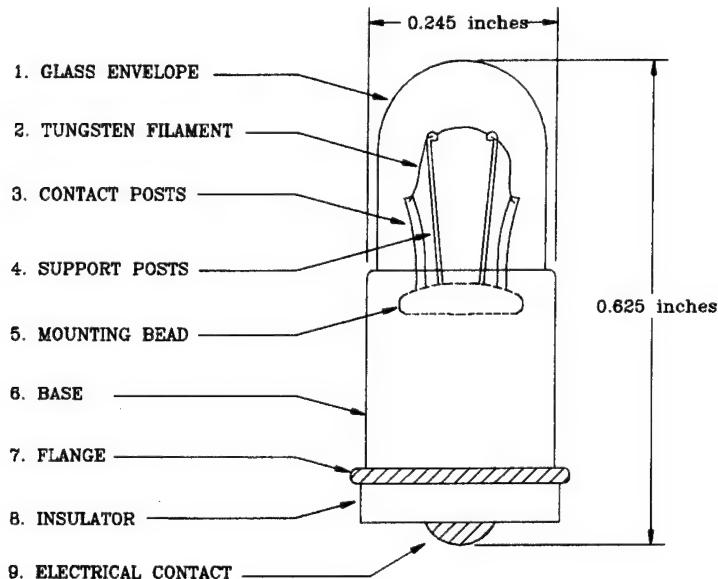
Topic	See Page
Construction	32
Lamp Data	34
Operating Relationships	36
Aging Mechanisms	37
Tungsten	39

CONSTRUCTION

Overview There are several common types of incandescent lamps used in military aircraft. Most of these operate on 28 Vdc and are used as instrument panel illuminators and warning indicators.

Construction The components of a typical incandescent indicator lamp for aircraft use are discussed below with reference to Figure 1.1.

Figure 1.1 Components of a small flange base incandescent lamp.



Glass Envelope The filament structure is surrounded by a glass envelope. The envelope is either evacuated or filled with an inert gas to prevent oxidation of the filament.

Tungsten Filament Incandescent lamp filaments are made from nearly pure Tungsten which is fabricated into wire form using a powder metallurgy process. The voltage and power requirements dictate the dimensions of the wire. In small lamps the wire is usually so long that it must be coiled or double coiled to fit in the envelope.

Contact Posts Contact posts provide the electrical attachment points for the ends of the filament. The posts must protrude through the envelope for external electrical connections. The posts are made of a special material called Dumet, a nickel-iron alloy with an outer coating of copper. The alloy has a coefficient of thermal expansion that closely matches that of glass; the copper coating provides a reliable seal to the envelope.

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CONSTRUCTION, Continued

Support Posts Although the contact posts are the primary means of mechanical support for the filament, many designs require additional supporting members. For example, the type 327 lamp has two support posts. Support posts are usually made of molybdenum, because of its high melting point - 2410°C (4730°F).

Mounting Bead A glass mounting bead is used to secure the contact posts to the lamp base.

Base Most lamps are equipped with a metal base to provide mechanical support for the glass envelope and its contents, as well as one of the electrical contacts. There are three types of bases:

Flange base lamps have a circumferential flange near the bottom of the base which helps hold the lamp in its socket.

Bayonet base lamps have two small posts on the base which mate with slots in the socket. This type of attachment requires a twisting motion to latch the lamp in place.

Baseless lamps have wire leads which are soldered directly to printed wiring boards or terminal strips.

Electrical Contacts Each style of lamp must have two electrical contacts. On baseless lamps the leads provide the two connections. On flange and bayonet base lamps the body of the metal base is one contact. A metal button mounted on an insulator at the bottom of the base is the other contact.

LAMP DATA

Overview Two kinds of lamp data are presented in the following tables. Table 1.1 list general ratings and characteristics of common 28V aircraft lamps. Table 1.2 provides specific data on the type 327, which is one of the most common lamps.

Table 1.1 Characteristics of 28V aircraft lamps.

Trade #	Amperes	MSCP	Bulb	Base	Length Inches	Dia. Inches	Filament	Life Hours	Military Standard
6839	0.024	0.13	T-1	SMF	0.360	0.160	CC-2F	500	MS3338-6839
327	0.040	0.34	T-13/4	MF	0.625	0.245	C-2F	4000	MS25237-327
387	0.040	0.30	T-13/4	MF	0.625	0.245	C-2F	7000	MS25237-387
313	0.170	3.50	T-31/4	MB	1.190	0.400	C-2F	500	MS25231-313
301	0.170	3.00	G-5	SCB	1.250	0.630	C-2F	500	MS25238-301
303	0.300	6.00	G-6	SCB	1.440	0.750	C-2F	500	MS15570-303
1495	0.300	6.00	T-41/2	SCMB	1.380	0.560	C-2F	500	MS25069-1495

LEGEND

BASES

SMF	Sub Midget Flange
MF	Midget Flange
MB	Miniature Bayonet
SCB	Single Contact Bayonet
SCMB	Single Contact Miniature Bayonet

FILAMENT STRUCTURE

C-2F	Coiled with 2 Support Posts
CC-2F	Coiled-coil with 2 Support Posts

Continued on next page

LAMP DATA, Continued

Table 1.2 Data on the Type 327 lamp.

Volts	28 V
Watts	1 W
MSCP	0.34
Operating Life (AC)	2,000 Hours
Operating Life (DC)	500 Hours
Overall Length	0.625 in
Diameter	0.245 in
Base Type	Button
Support Posts	2
Coil Structure	Single Coiled
Filament Wire Diameter	0.0003 in
Filament Wire Length	5 in

OPERATING RELATIONSHIPS

Overview The characteristics described below give the investigator a general understanding of the operating parameters of incandescent lamps [1.4, 1.5]. The equations may be used to predict the behavior of a lamp under certain abnormal conditions that can occur during a mishap.

Temperature Tungsten filaments operate at about 1650 °C. As a result, certain properties of the filament change dramatically at the operating temperature. For example:

- Resistance - can increase by about 10 times.
- Tensile strength - can decrease by about 20 times. This increases ductility.

Life Filament temperature and lamp life can be affected significantly by very small changes in operating voltage. The relationship between rated life and actual life under abnormal test conditions is generally expressed as:

$$LIFE = RATED LIFE \cdot \left(\frac{RATED VOLTAGE}{APPLIED VOLTAGE} \right)^{12}$$

This relationship highlights the importance of identifying any possible alterations in operating voltage which may have occurred during the life of the lamp or as part of the mishap.

Light Output Light output is measured in mean spherical candle power (MSCP). The relationship between rated MSCP and MSCP under abnormal voltage conditions is generally expressed as:

$$MSCP = RATED MSCP \cdot \left(\frac{APPLIED VOLTAGE}{RATED VOLTAGE} \right)^{3.5}$$

Load Current The expected increase in load current at increased voltages is suppressed somewhat by the associated increase in resistance at elevated temperatures. As a result, the current at abnormal applied voltage levels is expressed as:

$$CURRENT = RATED CURRENT \cdot \left(\frac{APPLIED VOLTAGE}{RATED VOLTAGE} \right)^{0.55}$$

AGING MECHANISMS

Overview All incandescent light bulbs eventually burn out. Failure is caused by a reduction in wire cross-section and an increase in brittleness, due to aging. The aging mechanisms are as follows:

- water driven ion migration (water cycle)
- recrystallization
- dc notching

Re-crystallization and dc notching are the two major aging mechanisms in aviation incandescent light bulbs.

Water Cycle The mechanism starts when a small amount of water vapor is trapped in the lamp during the manufacturing process. Water molecules hit the hot tungsten filament and disassociate into hydrogen and oxygen. The oxygen combines with the hot tungsten atoms to form tungsten oxide which evaporates and is deposited on the surface of the glass envelope. Due to the equilibrium reaction in effect, a certain amount of free oxygen is released which recombines with free hydrogen to form water again. Metallic tungsten is also released and deposited on the inside on the glass envelope.

The water acts as a catalyst in the process of removing tungsten atoms from the filament and depositing them on the glass envelope. Eventually, the silvery coating of tungsten on the envelope surface becomes thick enough to interfere with light transmission and can easily be detected with the naked eye.

Recrystallization Incandescent filaments operate at a temperature of about 1650 °C (3000 °F). Since the recrystallization temperature is about 1165 °C, recrystallization will normally take place when the lamp is ON.

Tungsten wire is made using a powder metallurgy process which results in a fine grain structure. When the filament is heated above the recrystallization temperature atoms from smaller grains move to larger grains at the grain boundaries. The result is that the smaller grains disappear and the larger grains expand. Examination of aged filaments by SEM have shown that single crystals can grow to a length of several coils. As the grains expand the filament becomes more brittle and susceptible to shock fracture.

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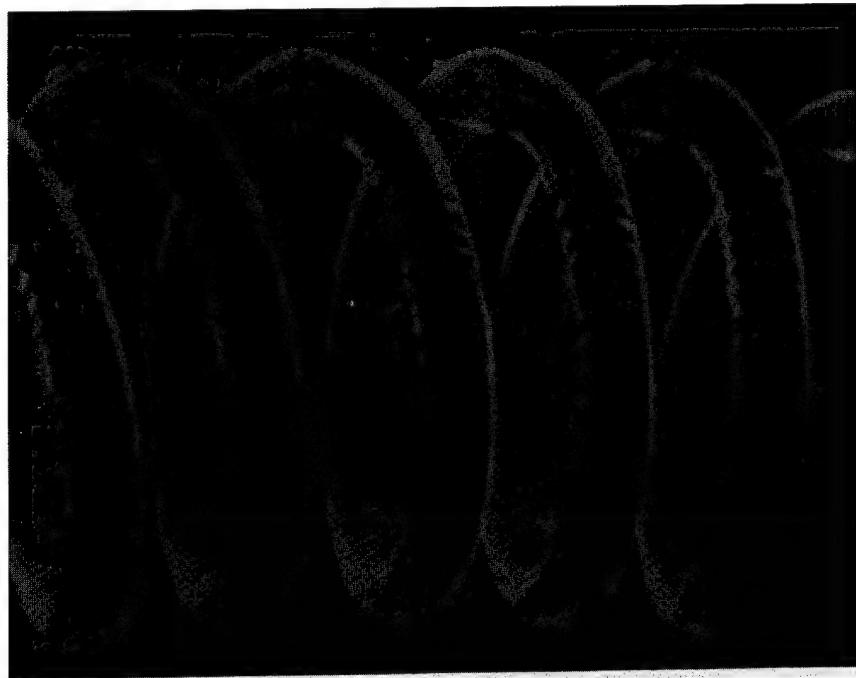
AGING MECHANISMS, Continued

DC Notching Most aircraft lamps operate on dc power and, as a result, current always flows through the filament in the same direction. This results in an aging process in which the smooth, round surface of the filament is changed into a saw-toothed jagged surface. This deformation imposes a variation of cross-sectional area on the filament.

The notching results in mechanical weak spots and hot spots of high resistance. The filament will eventually break because it is too weak to withstand any shock, or will burn out, because a local hot spot exceeds the melting temperature of tungsten.

Figure 1.2 shows notching on a filament wire which occurs when lamps are operated on dc.

Figure 1.2 Dc notching of filament wire. Magnification: about 250X.



TUNGSTEN

Overview The physical properties of tungsten are critical to incandescent lamp operation.

Filament Wire Incandescent lamp filaments are made of tungsten, usually 99.98% pure. The wire is made using a powder metallurgy process. The wire diameter is usually between 0.0002 inch and 0.005 inch. The length and diameter used for a particular lamp depend on several factors, including operating voltage, required light output, and physical size of the lamp.

Properties Tungsten has the best temperature, stiffness, and vapor pressure characteristics for incandescent lamp applications. The high stiffness of this element, especially at high temperatures, is also a very important characteristic. It prevents sagging and shorting out of the coils.

Table 1.3 lists some of the physical properties of tungsten.

Table 1.3

Physical Properties of Tungsten	
Atomic Symbol	W
Atomic #	74
Atomic Weight	183.85
Melting Point	3410 °C (6170 °F)
Re-crystallization Temperature	1165 °C (2130 °F)
Density	19.3 Mg/m ³
Resistance at 27 °C	5.7 $\mu\Omega$ -cm
Vapor Pressure at 2100 °C	8 x 10 ⁻⁹ mm Hg
Stiffness Modulus at 20 °C	60 x 10 ⁶ PSI

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TUNGSTEN, Continued

Resistance Table 1.4 shows the resistance of tungsten at different temperatures [1.6]. Note that the resistance increases about 10 times from 27 to 1827 °C.

Table 1.4 Resistance vs Temperature.

Temp °C	Resistance $\mu\Omega\text{-cm}$
27	5.7
327	13.1
627	21.4
927	30.3
1827	59.1
2727	90.4
3227	108.5

Tensile Strength Table 1.5 shows the tensile strength of tungsten at different temperatures [1.6]. Note that the tensile strength decreases to less than 1/20 its value from 21 to 1999 °C.

Table 1.5 Tensile Strength vs Temperature.

Temp °C	Strength PSI
21	430000
199	350000
399	320000
599	240000
999	100000
1999	20000
2799	5000

SECTION B

FAILURE CHARACTERISTICS

OVERVIEW

Overview This section covers the physical characteristics the mishap investigator is likely to encounter when examining incandescent lamps.

Contents This section includes the following topics.

Topic	See Page
Filament Deformation	42
Filament Fracture	46
Filament Oxidation	50
Support Post Deformation	53
Filament Burnout	55
Resonance Conditions	57

FILAMENT DEFORMATION

Observation	The presence of filament coil deformation is the most important factor in post-impact lamp analysis. It can be observed easily with low power optical microscopy.
Cause	Filament deformation usually occurs when a lamp is ON at the time of impact.
Mechanism	At the instant of impact the filament undergoes a sudden change in velocity. The momentum of the filament itself generates a reaction force that acts against the contact and support posts. If the acceleration is high enough and the filament is ON the most likely result is permanent deformation of the filament.
	Filament deformation occurs when the lamp is ON because the ductility of tungsten is higher at the incandescent temperature than it is at room temperature.
Precautions	A slight stretching of the filament is possible in some new lamps, even when OFF. This only occurs under severe impact conditions and can generally be contrasted to the severe stretch characteristic of lamps that were ON at the time of impact.
Discussion	Filament deformation characteristics can be described as: <p><u>Slight deformation</u> This usually appears as the opening up of a few coils of the filament near the support posts. The overall shape of the filament is not distorted.</p> <p><u>Major deformation</u> The general shape of the filament is distorted. The filament is stretched and deformed and some uncoiling has occurred.</p> <p><u>Resonance and entanglement</u> The filament vibrates wildly during short high-shock impacts and can become tangled and short out sections of itself. This condition is very reliable evidence that the lamp was ON at the time of impact.</p> <p><u>Local deformation</u> Local deformation is stretching that occurs in sections of a hot (ON) filament as a result of an impact. In severe impact, local deformation may also occur in a cold (OFF) filament due to resonance in the filament support posts.</p> <p><u>General deformation</u> Upon impact, general filament stretching may be noted on both OFF and ON lamp filaments.</p>

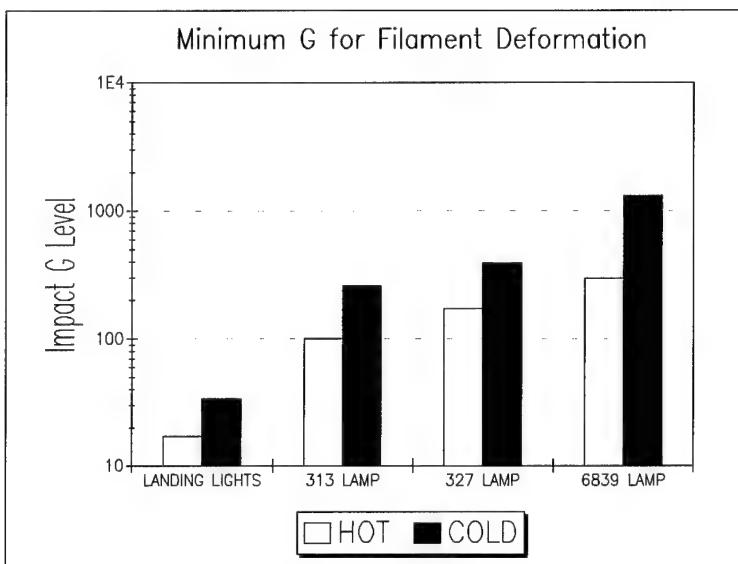
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FILAMENT DEFORMATION, Continued

Data In general, filament examination is most effective when a lamp is subjected to a single severe impact. In addition, there is a G level impact threshold for each type of lamp below which filament deformation is not likely to occur. These levels depend on whether the lamp is ON or OFF and are shown in Figure 1.3 for several types of lamps. The 327 lamp filament will usually not deform below about 300 G when ON and 500 G when OFF.

Another consideration is that impacts internal to the aircraft usually have higher G levels than those associated with the aircraft impacting the ground. For example, the instrument panel hitting a landing gear structure will generate high G levels. These internal impacts are more likely to cause filament deformation than the calculated ground impact G levels.

Figure 1.3 G Level thresholds for aircraft lamps.



Analysis Filament deformation itself can be examined with an optical microscope at magnifications of 10-20x for type 327 lamps. Smaller lamps require higher magnifications.

The examination of filament fracture usually requires SEM examination of the fracture surface. This examination is sometimes needed to verify lamp condition, in addition to filament deformation.

Examples Figure 1.4 and 1.5 show normal and deformed type 327 lamp filaments. Figures 1.6 and 1.7 show normal and deformed type 6839 lamp filaments.

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FILAMENT DEFORMATION EXAMPLES

Figure 1.4 Normal 327 lamp filament. Magnification 20X.

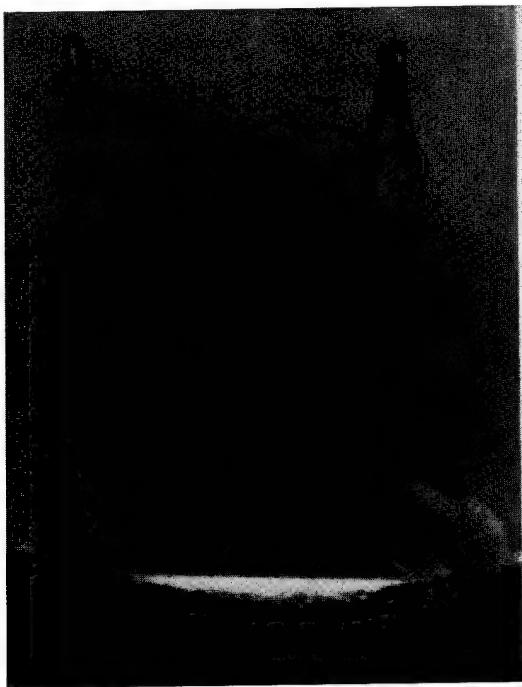
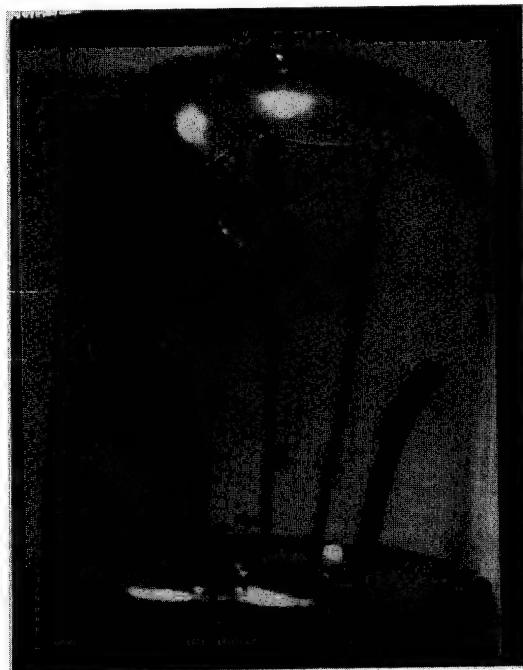


Figure 1.5 Typical deformation of an ON 327 lamp filament. Magnification 10X.



Continued on next page

FILAMENT DEFORMATION EXAMPLES

Figure 1.6 Normal 6839 lamp filament. Magnification about 7X.

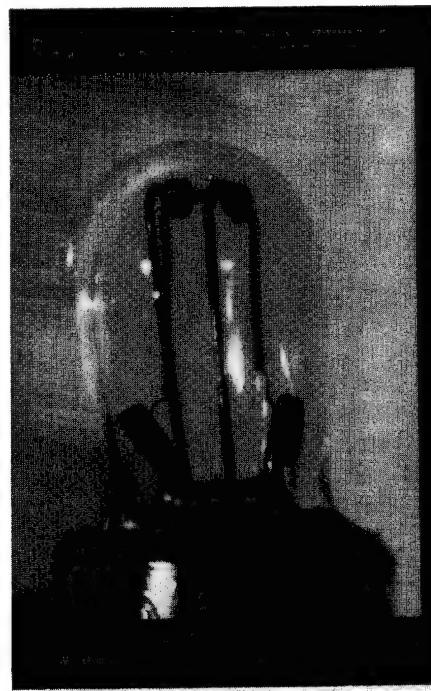
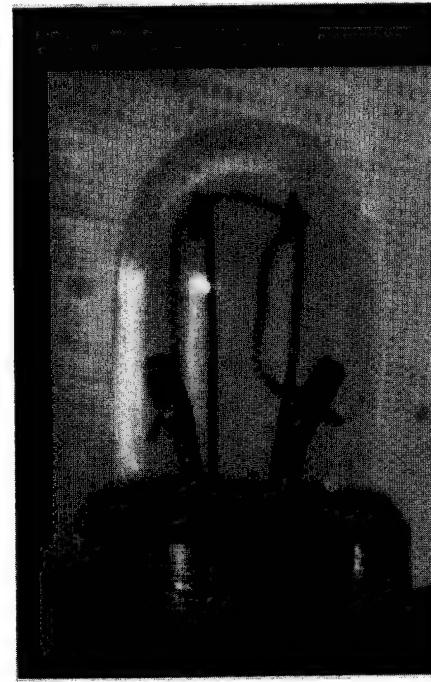


Figure 1.7 Typical deformation of an ON 6839 lamp filament. Magnification about 7X.



FILAMENT FRACTURE

Observation	Microscopic examination of filament fracture surfaces can provide additional evidence about whether an incandescent lamp was ON or OFF during impact.
Mechanism	During a severe impact the filament can be stretched to the point of failure. The mating surfaces of the failure site are called fracture surfaces. The characteristics of these surfaces indicate the type of fracture.
	Brittle fractures have sharp, cleaved edges on the fracture surface. Brittle fractures occur when metal is pulled apart very rapidly and does not have time to stretch. Brittle fractures are most common in lamps that are OFF during impact but can occur in lamps that are ON but have aged filaments.
	Ductile fractures occur when the metal is pulled apart more slowly and decreases in cross sectional area at the fracture site. The fracture has a characteristic "cup and cone" appearance and the surfaces have a fibrous appearance. Ductile fractures are not commonly found since melting generally obscures the characteristic appearance of the fracture surfaces.
	Melted fracture surfaces are specific to current-carrying conductor failures. Melting is caused by electric heating which increases as the conductor cross section area decreases during the fracture. It gives the fracture surfaces a smooth appearance. Melted fracture surfaces are a good indication a lamp was ON during impact.
Precautions	In cases where the filament has multiple fractures, it is important to determine which was the first fracture to occur. This is the one most useful factors in determining the lamp's condition during the impact.
	When a number of lamps are subjected to the same impact forces they should be analyzed as a group. This should include lamps that were known to be ON and those known to be OFF, in addition to the lamps to be analyzed. This provides more opportunity for cross checking, and more reliable results.
Cause	During a severe impact, forces on the filament can cause it to fracture. These fractures can occur in either the ON or OFF state.

Continued on next page

FILAMENT FRACTURE, Continued

Discussion **OFF during impact** - multiple brittle fractures are evidence of severe momentum forces on a cold filament. The older the filament, the more likely it will fracture in several places. Some impacts can be so substantial that the filament literally shatters into dozens of fragments.

ON during impact - melted fracture surfaces indicate that the lamp was ON during the impact. Uncoiling and short circuits are more common failure characteristics. If a lamp is aged and the impact forces are severe, then brittle fractures may still occur. Other indications that the lamp was ON may include secondary melting, oxidation, tungsten deposits, and dc notching.

Continued on next page

FILAMENT FRACTURE, Continued

Data The brittle transition temperature of tungsten is around 510 °C (950 °F). Lamp filaments operate at about 1650 °C (3000 °F).

Analysis If the filament is fractured the primary objective is to determine whether the initial fracture site was brittle or ductile.

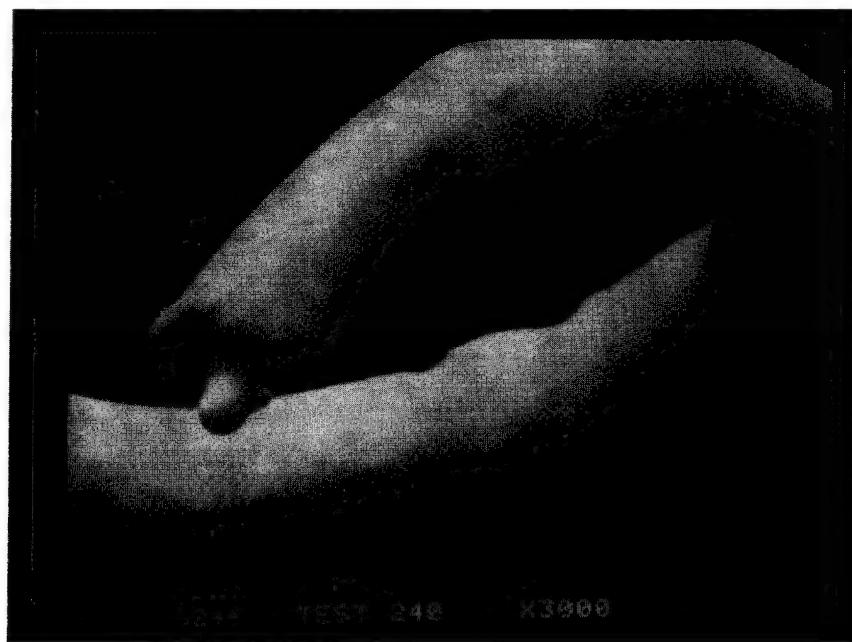
This examination is done with the SEM after the envelope is removed. A brittle fracture surface may indicate the lamp was OFF. Ductile or melted fracture surfaces are a good indicator that the lamp was ON.

Examples Melted fracture surfaces are shown in Figure 1.8.

Brittle fracture is illustrated in Figure 1.9.

Multiple brittle fracture is shown in Figure 1.10.

Figure 1.8 Ductile/melted fracture of type 327 lamp. Magnification is 3000X.



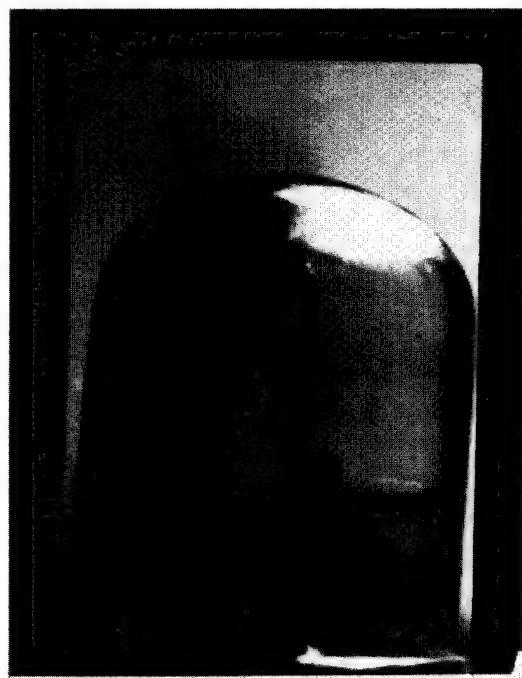
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FILAMENT FRACTURE, Continued

Figure 1.9 Brittle fracture of type 327 lamp. Magnification about 6000X.



Figure 1.10 Multiple brittle fracture of type 327 lamp. Magnification about 20X.



FILAMENT OXIDATION

Observation Oxidation of the tungsten filament can be observed microscopically and is a good indication that the lamp was ON at impact.

Cause Oxidation occurs when the envelope is fractured and the hot filament is exposed to air. Oxidation is a good indication that the lamp was ON at impact.

If the envelope is fractured and the filament is not oxidized the lamp was probably OFF at impact.

Mechanism When the glass envelope is broken while the filament is incandescent, the exposure to air (oxygen) causes rapid and profound oxidation of the filament wire. When the filament is cold and the envelope fails, no such oxidation occurs.

Precautions None.

Discussion The oxidation can manifest itself in caking and scaling of the wire surface when the filament is very hot. Color changes are also very common. Any such oxidation or discoloration is evidence that the filament was incandescent just prior to impact.

Characteristic changes in the filament that accompany oxidation are as follows:

- the color of metallic yellow, red, purple, or blue, depending on the temperature of the filament.
- scaling of the surface if the filament wire is incandescent.
- small glass fragments melting and adhering to the filament.

FILAMENT OXIDATION, Continued

Data At ambient temperature, tungsten is a steel-like light gray in color. Therefore, the surface color or scaling is a direct indication of the temperature of the tungsten at the time of oxidation and is a good indication the lamp was ON at impact.

The degree of oxidation depends on the temperature of the tungsten wire. At lower temperatures the surface shows the typical and distinct metallic coloration as listed in the following table:

°C	°F	Color
343	650	straw yellow
371	700	metallic orange
399	750	metallic red
427	800	metallic purple
454	850	metallic blue
482	900	dark blue
510	950	pale blue
538	1000	metallic gray blue
566	1050	metallic black blue

Above 538 °C (1000 °F), the tungsten surface exhibits scaling which is readily observable through a microscope.

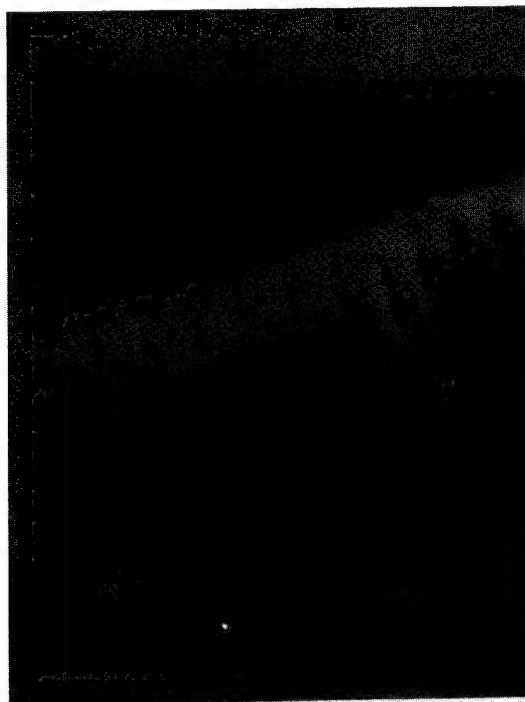
Analysis Analysis is conducted by optical microscopy.

Examples Figure 1.11 shows oxidation of a filament in a type 327 lamp.

Continued on next page

FILAMENT OXIDATION EXAMPLE

Figure 1.11 Oxidation of the filament in a type 327 lamp. Magnification about 500X.



SUPPORT POST DEFORMATION

Observation	Support post deformation can be observed during post-impact examination of incandescent lamps. It is an indicator of severe impact conditions, but does not otherwise provide information about the ON or OFF state of the lamp.
Cause	Support post deformation is caused by severe impact loads.
Mechanism	The support posts in a 327 bulb are typically made from molybdenum wire, because of its stiffness and relatively high melting point. Any deformation of the support post within the glass envelope is typically caused by severe resonant vibrations as the result of the impact excitation. The deformation attests to the severity of the impact, but does not indicate the state of the lamp.
Precautions	None.
Discussion	The impact forces and the resulting vibrations of the support post in the 327 bulb sometimes cause microscopic pieces of glass to break off and "float" around in the envelope during the impact sequence. The support posts are held in place by a bead of glass melted around them. At this interface the glass fragments are broken off by the forces of the impact. If the filament is hot, the glass fragments may adhere or melt into the filament wire. This can be observed microscopically and indicates that the lamp was ON at the time of impact.
Data	None.
Analysis	Optical microscopy is the most effective tool.
Examples	Figure 1.12 shows a typical example of support post deformation.

Continued on next page

SUPPORT POST DEFORMATION EXAMPLE

Figure 1.12 A typical example of support post deformation. Magnification about 15X. Note that one of the contact posts is also deformed.



FILAMENT BURNOUT

Observation	Filament burnout can be observed by visual or microscopic examination and provides supporting data about the impact condition of the lamp. It is usually, but not always, an indication that the lamp was ON at impact.
Cause	There are three different causes of filament burnout: <ul style="list-style-type: none">• circuit voltage too high• reduction of filament wire cross-section due to aging• shorting of a filament section due to flailing of the filament
Mechanism	Filament burnout can be caused by the three mechanisms discussed above. In most investigations only the last mechanism is of interest. It occurs when the filament gets entangled in itself and shorts out a part of its coil. The remainder of the coil gets an excessive current load and melts the tungsten wire while it is still subjected to the inertial load. This can cause the near molten tungsten wire to stretch, neck, and break in a ductile manner.
Precautions	Filament burnout can be caused by the three mechanisms discussed above, but only the last mechanism indicates that the lamp was ON at impact. Therefore, it is important to rule out the first two mechanisms before drawing any conclusion about the state of the lamp.
Discussion	Filament burnout from entanglement and shorting can often be recognized by the presence of small sections of coil melted into other sections of coil. Burning out or melting of the filament can be readily recognized by the presence of melt balls at the fracture end of the filament wire. Thinning of the filament wire into a needle-like tip is also evidence of melting. Burnout due to overvoltage has characteristic similar to those of short-circuit conditions, except for the lack of severe deformation. Burnout due to aging is often accompanied by notching like the kind shown in Figure 1.2.
Data	None.
Analysis	Analysis may be conducted by optical microscopy, but SEM is sometimes needed to verify the geometry of the burned filament ends.

Continued on next page

FILAMENT BURNOUT, Continued

Examples Figure 1.13 shows a filament that burned out from an overvoltage condition. Notching is also apparent. Figure 1.14 shows filament burnout resulting from partial entanglement and continued impact load. Melted balls of tungsten can also be seen.

Figure 1.13 Filament burned out from an overvoltage condition. Magnification about 167X.

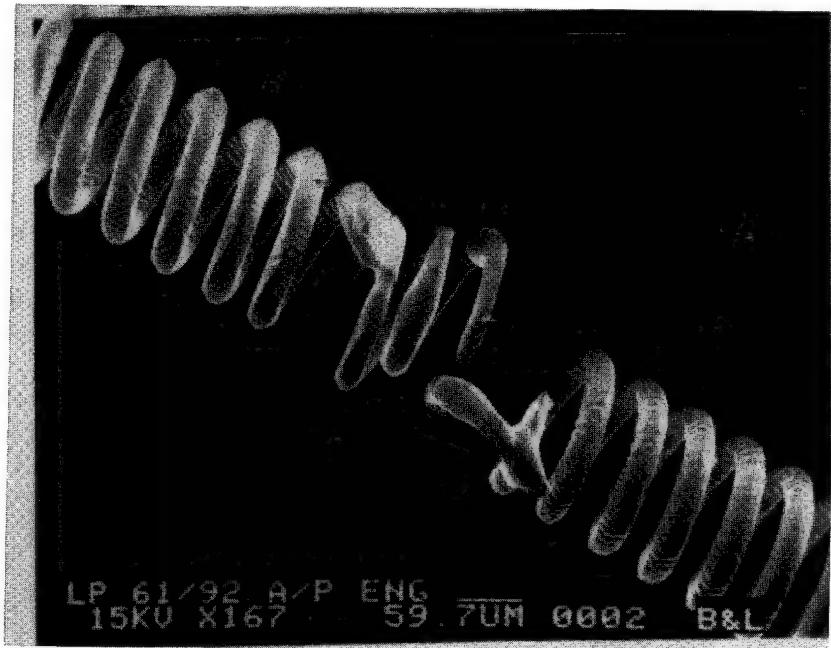
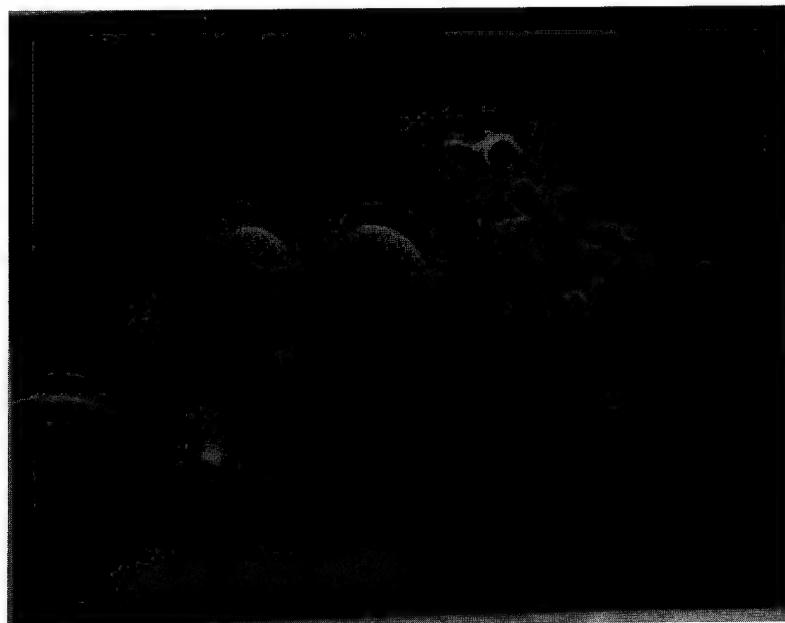


Figure 1.14 Filament burned out from entanglement, shorting and continued impact load. Magnification about 160X.



RESONANCE CONDITIONS

Observation	Filament and support post resonance results in severe tangling and deformation of the filament. The condition can be observed during microscopic examination.
Cause	Resonance is caused by severe short-duration impacts.
Mechanism	During the impact sequence, the short-duration inertia force pulse excites the support posts which then start vibrating. The vibration can stretch the filament in the areas near the support posts. If the vibration of the posts is strong enough, it can flail the entire filament within the confines of the glass envelope.
Precautions	None.
Discussion	The effect on the filament depends on the severity of the vibration and the status of the filament. When the filament is cold, the stretching forces may cause: <ul style="list-style-type: none"> • no damage at all; • fracture of the filament near the support posts; • multiple fractures if force is severe enough. When the filament is hot, the stretching force may cause: <ul style="list-style-type: none"> • mild stretching near the support posts; • stretching all along the filament; • severe stretching and entanglement of the filament coil; • severe stretching and ductile fracture.
Data	Tests have shown that the resonant frequencies of the support posts and filament of the type 327 lamp are in the range of 350 Hz and 1350 Hz respectively.
Analysis	Analysis is usually conducted by optical microscopy.
Examples	Severe stretching and entanglement of the filament is shown in Figures 1.15 and 1.16 and is caused by whipping of the support posts.

Continued on next page

RESONANCE CONDITIONS EXAMPLES

Figure 1.15 Entanglement caused by resonance condition in type 327 lamp. Magnification about 8X.

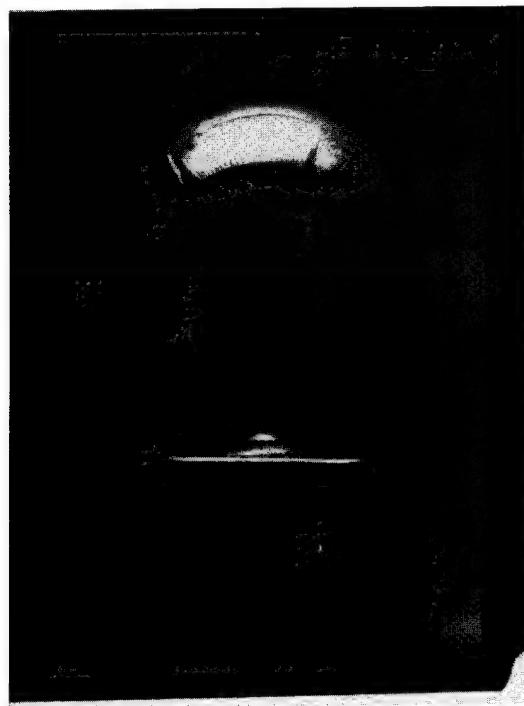
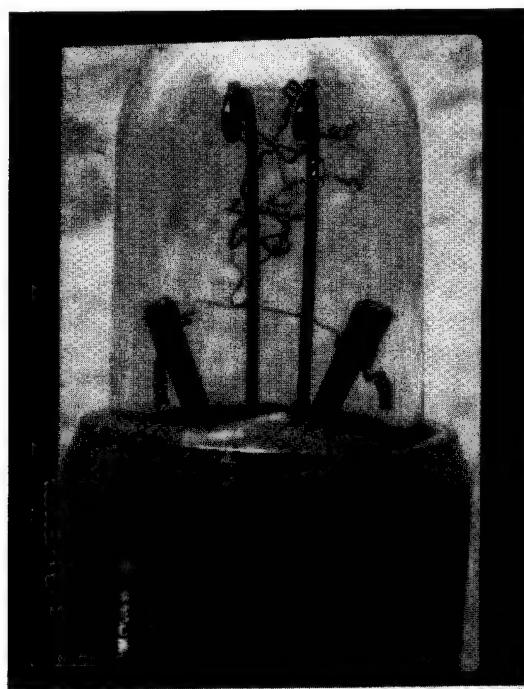


Figure 1.16 Entanglement caused by resonance condition in type 6839 lamp. Magnification about 10X.



SECTION C

FAILURE ANALYSIS PROCEDURES

OVERVIEW

Introduction There are three main reasons to analyze lamps during mishap investigation:

1. To determine whether electrical power was present at the time of impact.
2. To determine whether annulciator, warning or function lamps were ON or OFF at the time of impact.
3. To determine the severity of impact forces.

Lamp analysis is only meaningful if the G levels are high enough to cause filament deformation in a lamp that was known to be ON at impact.

Contents This section includes the following topics.

Topic	See Page
Field Examination	60
Laboratory Examination	62
Photography and Documentation	64
Determining ON or OFF Condition at Impact	66
Examination Checklist	68

FIELD EXAMINATION

Introduction A 7 to 10x loupe with proper lighting is sufficient for effective examination of lamp filaments in the field.

No preparation other than wiping the glass envelope clean is required for field examination.

Lamp removal and examination are best done under laboratory conditions, but field procedures are outlined in this article if the examination must be done in the field.

Removal The lamps should only be removed in a clean, safe area, with sufficient table space and after proper preparation to insure that the identification of the lamps is maintained. A small flat tip screwdriver should be used for prying. It is useful to have a stereo microscope handy to examine the lamp prior to storage in the tagged container, and to make a record of initial observations.

Documentation If lamps are removed in the field, it is critical that their location and condition be documented prior to shipment and later laboratory examination.

It is also very important to make some observation about the condition of the lamp or filament before it is shipped for laboratory examination. In some cases this data may not be shared with the laboratory but should be retained by field personnel for later confirmation of laboratory results.

A record of the condition and location of all panels should be made prior to removal from the site. Duplicate photographic records are recommended.

The observed damage to the instrument panel, right down to the filaments themselves, must be described. For example, the fact that the left hand top corner of the instrument panel is completely ripped off is an indication that the impact forces were severe enough to make lamp analysis a useful exercise. A description with photographs should become a part of the report on the lamp analysis.

Field Examination Checklist The instrument panels of an aircraft contain many dozens, if not hundreds, of lamps. Consequently, it would be very cumbersome to document the damage to each lamp and its filament in descriptive sentences. A convenient and effective short cut is a prepared checklist that can be ticked off in the appropriate places to define the observed damage in each lamp. Table 1.6 is a sample identification checklist that can be copied and filled out for each lamp removed for analysis.

Continued on next page

FIELD EXAMINATION, Continued

Transportation Transportation of lamps or instrument panels containing lamps is relatively straightforward. Identification and tagging is of the utmost importance. Normal packaging techniques are sufficient. Instrument panels or components containing lamps should be wrapped with impact-absorbing paper or bubble sheet to protect them from damage during shipment.

Precautions It is not advisable to remove a lamp from its location in the instrument, switch or annunciator panel while it is still in the wreckage. The conditions at the mishap site are typically too precarious to safely remove, tag and store these very small lamps. Instruments, switches, warning lamps and annunciator panels should be removed in their entirety and the lamps examined under laboratory conditions.

If lamps must be examined in the field, care should be taken to remove only one lamp at a time, and to return it to its location immediately after examination. If it is not possible to return the lamp to its original location, it should be stored and tagged as described later in this section.

Lamps with damaged envelopes should not be removed in the field.

Table 1.6 Sample Lamp Identification Form

Aircraft	<i>F15</i>
Sample ID#	<i>LAMP 201</i>
Date of Mishap	<i>04/30/90</i>
Date Removed from Site	<i>04/30/90</i>
Location Found At Site	<i>Front Cockpit Instrument Panel Lower Right</i>
Function Indicated	<i>LH Generator</i>
Number of Lamps in Indicator	<i>2</i>
Type	<i>327</i>
Envelope Condition (Lamp 1,2)	<i>Intact, Intact</i>
Filament Condition (Lamp 1,2)	<i>Severly deformed, Severly deformed</i>
Comments	<i>Indicator lens covered with soot</i>
Impact Conditions	<i>Single severe ground impact</i>

LABORATORY EXAMINATION

Preparation Soot and glass surface oxidation adversely affect the transparency of the envelope for examination. Vigorous cleaning of the lamp in methanol or detergents can often restore sufficient transparency to the glass to observe and photograph the filament. Care should be taken not to disturb or damage the filaments.

Securing the lamp on a temporary base using wax, putty, modelling clay, or glue can make it easier to handle and stabilize for microscopic examination.

Microscopic Examination Lamps can be examined effectively with a stereo microscope at magnifications of 7 to 50 times. At lower magnifications, the lamp can be held in the hand while viewing. At higher magnifications filament shaking due to insecure mounting, table or floor vibration limits definition. Also, poor optical quality of the glass envelope may impair visibility.

When the filament is shattered or broken in many pieces, the lamp may need to be tapped while upside down to shake the filament fragments into the top of the glass envelope to make them visible.

Occasionally it is practical to examine and analyze the filament in more detail, to determine fracture type or look for glass fragment adhesion. Also, a definitive photograph is occasionally required for documentation. In these cases, it may be practical to remove the glass envelope for SEM analysis and additional microscopic analysis.

Envelope Removal Envelope removal is not difficult but practice and care are required before the investigator becomes confident with the procedure. The recommended procedure is as follows:

1. Score the envelope all around at the base with a diamond or carbide scribe or the type of file used for cutting laboratory glassware.
2. Hold the lamp with the envelope down and gently squeeze the metal base with a pair of needle nosed pliers. This is illustrated in Figure 1.17. The pressure applied to the metal base deforms the base and applies a stress to the envelope around the circumference where the score has been made. The envelope will fracture at the scratch and will drop off without touching the filament.

Continued on next page

LABORATORY EXAMINATION, Continued

SEM Examination SEM examination requires the removal of the glass envelope and the secure mounting of the lamp's base onto a special pallet. The steps for mounting are as follows:

1. Before mounting on the SEM pallet, the filament should be carefully examined with a stereo microscope to decide what has to be viewed in the SEM and in which position the lamp has to be mounted on the pallet.
2. Mounting the specimen can be done effectively with a small amount of glue. The base is then partially covered with Carbon paint to establish an electrical path from the base contacts to the pallet.
3. The pallets are stored in special boxes until ready for mounting in the SEM vacuum chamber for viewing.

Storage Once the envelope has been removed the lamps can be stored in small boxes which have foam rubber inserts in the bottom. The rubber may be slotted to accept the base and the lamps inserted with the filament facing up.

Lamps can also be stored in short pieces of clear plastic tubing. The lamps are inserted into the tubing so that the filament is facing in and the tubing makes a snug fit with the base. This method protects the filament and support posts from damage and captures any pieces of filament that may become loose during storage.

Figure 1.17 Method of squeezing lamp base with pliers to remove envelope.



PHOTOGRAPHY AND DOCUMENTATION

Introduction Because all aircraft lamps look the same to the uninitiated, evidence photographs should be presented in a series of increasing detail. This is necessary to provide the background and supporting evidence which will be needed in later stages of the investigation.

For example, photographs of a warning lamp found to be ON at impact should include the following:

- the location of the lamp on the instrument panel
- the significant damage that caused the filament to stretch
- the warning lamp itself
- the whole filament
- the close-up detail of the significant filament stretch

It is a good idea to keep a written log of the photos while they are being taken. This will help in identifying the individual lamps after the photographs are developed and a report is being prepared.

Photographic Equipment With practice, good photographs can be made in the field using portable equipment. An interchangeable lens, 35 mm, single-lens reflex camera is recommended. A 50 mm macro lens, a small tripod, remote shutter release, and a light source will also be needed. Almost all modern cameras of this type have integral light meters so that good exposure can be obtained using a variety of lighting methods.

A so-called "macro" lens is capable of focusing much closer than normal lenses. Some are capable of 1:1 magnification at the film plane. A bellows attachment or extension tubes can be used for further magnification. A bellows attachment will allow up to 3 or 4X magnification with the 50 mm macro lens, and the magnification is continuously variable.

A portable light source should be used when insufficient light is available. One or two incandescent lamps may be the best choice for control and convenience. Flash accessories may take acceptable photographs but do not provide the lighting necessary for proper focusing and examination before taking the photograph.

A tripod or other stand to hold the camera securely, and a remote shutter release are absolutely necessary to obtain sharp photographs.

An accessory which imprints time, date and other information on each frame is helpful.

Continued on next page

PHOTOGRAPHY AND DOCUMENTATION, Continued

Labeling Each bag or container for each lamp or lamp pair should be identified or tagged with the following:

- mishap number or reference
- lamp function
- location
- reference to photos taken

It should be emphasized again that maintaining identification of the items examined throughout the investigation is crucial.

Identification Since the typical modern aircraft instrument panel contains hundreds of small lamps of only a few different types, it is of the utmost importance to maintain proper identification for each lamp at all times. Before removal, lamps should be identified by their location and function. A properly identified container should be ready prior to removal of any lamp.

The simplest containers are small plastic zip-lock bags on which an identification code is written with indelible felt-tipped pen. During examination of a batch of lamps, only one lamp or pair of lamps having a single identification should be removed from its container or bag at any one time.

DETERMINING ON OR OFF CONDITION AT IMPACT

Introduction The general procedure for determining the state of a lamp is outlined in this article. The way that lamp filaments deform and break depends on lamp age, the severity of the impact, and other factors. Therefore, it is recommended that several lamps be examined when determining the state of any one lamp. The more lamps that are examined, the more reliable the analysis becomes.

ON at Impact If a lamp has one or more of the following characteristics it indicates that the lamp was probably ON at impact:

- filament stretch
- ductile deformation of filament
- filament melting
- filament wire ductile fracture
- filament wire discoloration
- filament oxidation
- glass fragments melted onto the filament

OFF at Impact If a lamp has one or more of the following characteristics it indicates that the lamp was probably OFF at impact:

- brittle fracture of filament
- shattering of filament
- no damage (only if other lamps in the panel show deformation)

Precautions It is important to find at least one lamp with filament deformation of some type to establish that the G levels were high enough for the analysis to be meaningful. It is also a good idea to establish that the lamp was ON at impact to rule out the possibility that the lamp was deformed from some prior event.

Two Lamp Indicators Most panel indicators contain two lamps, especially those using type 327 lamps. It is not uncommon to discover that the two lamp filaments have distinctly different conditions. For example, one lamp may show severe filament deformation while the other shows a brittle fracture and no signs of deformation. In this case it may be reasonably assumed that the second lamp burned out prior to impact.

Continued on next page

DETERMINING ON OR OFF CONDITION AT IMPACT, Continued

Examples The following examples are provided to illustrate the general rationale for analysis and the importance of examining several lamps.

Example 1: Two lamp indicator. One filament is deformed and the filament of the other lamp shows a brittle fracture. Assuming both lamps were supposed to be in the same state suggests that the first lamp was ON, but the second lamp burned out prior to the mishap.

Example 2: A pair of lamps in one indicator both show filament deformation but other lamps in the same panel have brittle fractures, or no deformation. This reinforces the conclusion that the lamps with the deformed filaments were ON and the fact that others were OFF at impact.

Example 3: Only one lamp is available for examination and it shows extensive filament deformation. This evidence stands alone and is a reliable indication that the lamp was ON at impact.

Example 4: Several lamps in the same panel show mild filament deformation but one lamp has a brittle filament fracture. In this case the age of that one lamp is in question. If tungsten deposits or dc notching are found these facts suggest that the lamp may have been ON at impact, and the brittle fracture attributed to its age.

EXAMINATION CHECKLIST

Introduction The checklist below is a comprehensive list of the characteristics that may be observed when examining incandescent lamps. The characteristics are grouped according to the lamp state with which they are most commonly associated. This list is offered only as a guide. It does not lead to a conclusion by itself, but should be reviewed before any examination is completed.

Table 1.7 Lamp Examination Checklist

Lamp Identification	
ID#	
Function	
Type	
Envelope Conditions	
Envelope Intact	
Envelope Damaged	
Filament Conditions - ON	
Stretched	
Uncoiled	
Tangled	
Ductile Deformation	
Melting	
Ductile Fracture	
Discoloration	
Oxidation	
Filament Conditions - OFF	
Brittle Fracture	
Shattering	
No Damage	
Lamp Age	
gsten deposits on envelope	
DC Notching of Filament	

SECTION D

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CHAPTER 2

WIRING

OVERVIEW

Introduction Wire is damaged in different ways by a variety of fundamental mechanisms. In a broad sense damage to wire is caused by one of the following three failure conditions:

- electrical
- mechanical
- fire

In this chapter we distinguish failure characteristics from failure conditions.

Failure Characteristics are the physical features which the investigator may examine or test for. This physical evidence may be used to infer the conditions present before/during/after an event. Each failure characteristic will have associated with it one or more sets of possible conditions called "failure conditions". Failure characteristics are covered in Section B.

Failure Conditions are the mechanisms which caused the damage. The investigator will use the evidence to try to determine which failure conditions were actually present during the mishap. Guidelines for determining the failure condition are covered in Section C.

Aircraft Wire This chapter deals with the type of wire classified as "hookup" wire, which is the largest class of wire used in aircraft. Only copper hookup wire is considered, since little aluminum is used.

Hookup wire is used for interconnect cabling between pieces of equipment, harnesses attached to the airframe, and for interconnect wiring inside equipment.

In addition to hookup wire, other types of wiring used include:

- multiconductor cabling
- high voltage cables
- special purpose data cables
- shielded coaxial or multiaxial cables

The techniques in this chapter may be applied to these types of wiring as well, depending on the specific circumstances.

Continued on next page

OVERVIEW, Continued

Contents This chapter is divided into four sections.

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SECTION A

BACKGROUND

OVERVIEW

Background This section provides general background information on the fabrication and properties of copper wire for military aircraft use. A summary of the manufacturing process covers the purpose of each element of finished wire.

Typical properties of military aircraft wire are included. A list of common insulation materials and the corresponding military standards can be used for identifying types of aircraft wire.

Contents This section contains the following topics:

- Manufacturing Process
- Data on MIL-W-81381 wire
- Insulation Materials

MANUFACTURING PROCESS

Summary The properties of finished copper wire are the result of a number of processing steps which begin with the final steps of processing copper ore itself. The last step in processing the ore results in a product which is at least 99.5% copper.

The processed ore is cast into ingots. These are used as anodes and electrolytically refined. The copper is transferred in the process onto cathodes which are at least 99.95% pure copper. These copper cathodes are the end product of the copper producing companies.

The cathodes are melted and cast into wire bars, followed by hot-rolling into wire rod. Continuous casting is also used to produce wire rod directly from the cathodes.

Wire rod is cold drawn through a series of dies until it is reduced to the proper diameter. Cold working during the drawing process causes a reduction in grain size and an elongation of the crystal grain structure.

Table 2.1 lists the properties of pure copper [2.1]. An example showing the grain structure of copper wire appears in Figure 2.2.

Alloys Two copper alloys are used in aircraft.

Oxygen free high conductivity, or OFHC, copper is made by induction melting prime quality copper cathodes. The heating is done in a non-oxidizing environment. It is produced by using a granulated graphite bath covering the copper and a protective reducing atmosphere that is low in hydrogen. OFHC is at least 99.99% pure copper and has an annealing temperature of 700-1200°F (370 - 650°C).

High strength copper alloy, or HSCA, is usually a cadmium-copper or cadmium-chromium-copper alloy. The alloy has improved mechanical properties including increased tensile strength and resistance to annealing at elevated temperatures. HSCA has an annealing temperature of 1000-1400°F (535 - 760°C).

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MANUFACTURING PROCESS, Continued

Coatings Copper wire used in aircraft is coated to provide environmental protection and to promote better connections. The coatings are applied to the individual strands of the conductor, usually by electroplating. The required minimum thickness for the most common coating materials is listed below:

- Silver 40 Microinches
- Nickel 50 Microinches
- Tin 30 Microinches

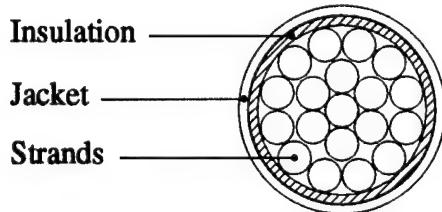
Stranding Aircraft wire is stranded to provide flexibility. The stranding arrangements are similar to those used for general purpose electronic hookup wire.

Concentric lay stranding is used for the smaller wire sizes, usually below AWG 10. In this arrangement, a central strand is surrounded by one or more layers of helically wound strands.

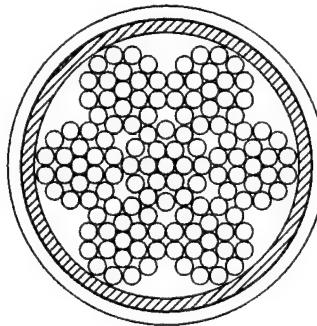
Rope lay stranding is used for larger wire sizes. In this arrangement a stranded central wire is surrounded by one or more layers of helically wound stranded wires.

Figure 2.1 Stranding Arrangements

Concentric Lay



Rope Lay



Continued on next page

MANUFACTURING PROCESS, Continued

Insulation Stranded conductors are provided with insulated coverings which provide environmental and mechanical protection, as well as electrical insulation. Almost all aircraft wire uses polymeric insulation materials. Glass braid, glass tape and other materials are used to a lesser extent.

Insulation materials can be applied by two processes. They are:

Extrusion is a process in which the plastic insulation material is melted and forced over the finished conductor under pressure as the conductor is pulled through a die.

Tape-wound insulation uses two layers of tape spiral wound around the bare conductor in opposite directions. A resin coating is usually applied to seal the finished tape-wound insulation.

Jacket materials are applied over the insulation for additional mechanical protection of the insulation and conductor.

DATA ON COPPER WIRE

Summary Reference data on copper and copper wire are presented in the following tables:

- Table 2.1 presents data on properties of copper.
- Table 2.2 presents data on copper wires.

Table 2.1 Properties of copper.

Atomic ID	Cu
Atomic #	29
Melting Point	1083 $^{\circ}$ C
Boiling Point	2595 $^{\circ}$ C
Density	8.96 g/cm ³
Resistivity	1.72 x 10 ⁻⁶ ohms cm
Temperature Coefficient of Resistance	0.0039/ $^{\circ}$ C
Temperature Coefficient of Expansion	16.5 x 10 ⁻⁶ / $^{\circ}$ C

Continued on next page

DATA ON COPPER WIRE, Continued**Table 2.2** Data on Standard Conductors from MIL-W-81381.

Wire Size	Nominal Area (Cir. mils)	Stranding	Strand Diameter (inch)	Conductor Diameter (inch)	Resistance (Ohms/1000')
30	112	7 x 38	0.0040	0.012	100.700
28	175	7 x 36	0.0050	0.015	63.800
26	304	19 x 38	0.0040	0.020	38.400
24	475	19 x 36	0.0050	0.025	24.300
22	754	19 x 34	0.0063	0.032	15.100
20	1216	19 x 32	0.0080	0.040	9.190
18	1900	19 x 30	0.0100	0.050	5.790
16	2426	19 x 29	0.0113	0.057	4.520
14	3831	19 x 27	0.0142	0.072	2.880
12	5874	37 x 28	0.0126	0.089	1.900
10	9354	37 x 26	0.0159	0.112	1.190
8	16983	133 x 29	0.0113	0.169	0.658
6	26818	133 x 27	0.0142	0.213	0.418
4	42615	133 x 25	0.0179	0.268	0.264
2	66500	665 x 30	0.0100	0.340	0.170
1	81700	817 x 30	0.0100	0.380	0.139
0	104500	1045 x 30	0.0100	0.425	0.108
00	133000	1330 x 30	0.0100	0.475	0.085
000	166500	1665 x 30	0.0100	0.540	0.068
0000	210900	2109 x 30	0.0100	0.605	0.054

INSULATION AND JACKET MATERIALS

Summary Reference data on MIL-Standard insulation and jacket materials is presented in the tables below:

Table 2.3 Insulation Materials for Military Aircraft Wiring.

Material	Trade Name	Military Standard
Extruded PVC		MIL-W-16878, 5086
Fluorocarbon Polyimide Tape	Kapton	MIL-W-81381
PTFE Tape	Teflon	MIL-W-22759
Extruded PTFE Tape	Teflon	MIL-W-22759
Extruded ETFE Tape	Tefzel	MIL-W-22759
Polyalkene		MIL-W-81044

Table 2.4 Jacket Materials for Military Aircraft Wiring.

Material	Trade Name	Military Standard
Glass Braid		MIL-W-81381, 5086
TFE Coated Glass Braid		MIL-W-22759
Extruded PVC		MIL-W-5086
Extruded Polyimide	Nylon	MIL-W-16878, 5086
Extruded Polyvinylidene	Kynar	MIL-W-22759
TFE Tape	Teflon	MIL-W-22759
Polyimide Coating		MIL-W-22759
Aromatic Polyimide Resin	"Liquid H"	MIL-W-81381

Legend PVC: PolyvinylChloride, TFE: Tetrafluoroethylene, PTFE: Polytetrafluoroethylene, ETFE: Ethylene Tetrafluoroethylene.

Reference Information on other insulating materials and their properties can be found in [2.2]. Properties of Polyimide can be found in [2.3].

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SECTION B

FAILURE CHARACTERISTICS

OVERVIEW

Introduction Specific failure characteristics may be observed which will help identify the failure condition of a particular wire.

Application The failure characteristics should be distinguished from the failure condition since there is not a one-to-one relationship between the conditions and the resulting characteristics. For example, recrystallization can result from electrical overcurrent conditions or fire exposure.

Discussion Several of the damage characteristics can appear in non-uniform areas. For example, less than one inch of wire may be damaged. In other cases the damage is uniform over a larger area sometimes up to several feet of length. Whether or not the damage is uniform can help verify the failure mechanism at work.

Failure Characteristics The failure characteristics covered in this section are listed below. These will be associated with failure conditions in Section C of this chapter.

- Recrystallization
- Beaded Wire Ends
- Metal Transfer
- Cup-and-Cone Fracture
- Insulation Failure
- Thermal Damage to Insulation
- Conductor Discoloration

RECRYSTALLIZATION

Observation The process of cold drawing copper wire results in a reduction in grain size and an elongation of the crystal grain structure along the axis of the wire.

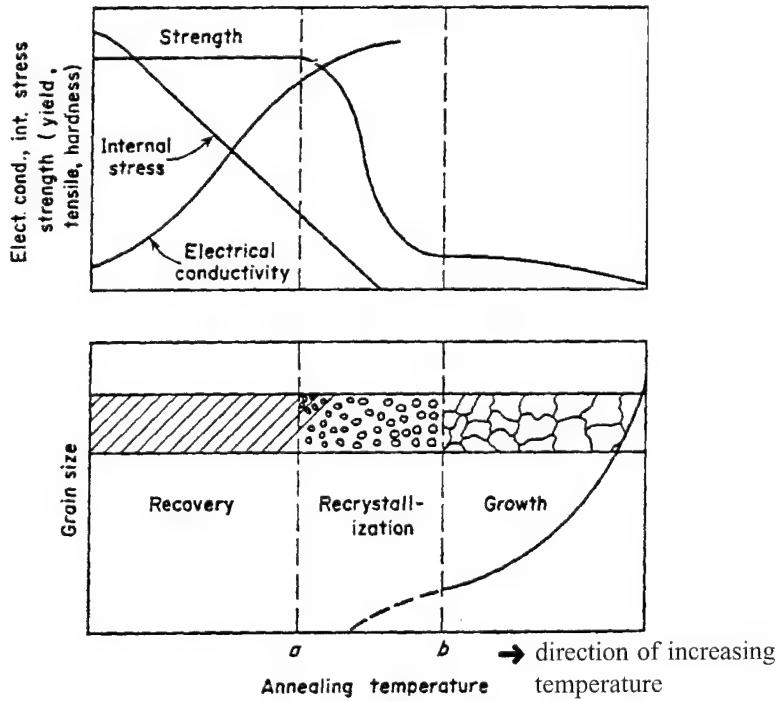
If the wire is subsequently heated to the recrystallization temperature, the grain structure undergoes a transformation. The change in grain structure can be observed in a microscopic photograph of a properly prepared wire cross-section.

Cause Electrical overheating, fire damage.

Mechanism If a metal, such as copper, has been formed into a shape by rolling, bending, or other cold forming process, it is said to be plastically deformed. In the process of plastic deformation the grains of the material are deformed and oriented, giving that material properties characteristic of cold forming. These properties are high strength and ductility.

If a plastically deformed metal is heated, three temperature dependent transitions are observed. These are recovery, recrystallization and growth. They are illustrated in Figure 2.2 [2.4]:

Figure 2.2 Recrystallization process.



Continued on next page

RECRYSTALLIZATION, Continued

Mechanism (cont'd) As the temperature increases toward "a" the material undergoes *Recovery*. Internal stresses are relieved and electrical conductivity increases. There is little observable change to the grain structure. Material strength is unaffected.

At temperature "a" *Recrystallization* begins. In this phase the oriented, distorted grains of the metal are gradually replaced with new grains that are small in size and equiaxed (i.e. same size in all directions). Internal stress is further relieved and material strength decreases.

If the temperature is increased to "b", recrystallization is complete with all pre-existing grains replaced with small, equiaxed, stress-free grains.

Further increase in temperature beyond "b" will begin a new transition where the grains increase in size. This process, called *Growth*, is associated with further decrease in the material strength and ductility until the material properties become that of raw, unworked metal.

The grain structure changes during recrystallization and growth may be observed in a properly prepared microscopic examination. This may provide evidence that the material was exposed to elevated temperatures for a period of time.

Precautions Recrystallization in copper wire occurs at temperatures as low as 700°F (370°C). Care is required in the preparations of samples for analysis so that the wire is not recrystallized by the experimental procedures.

Discussion The process of cold drawing copper wire results in a grain structure which is elongated along the axis of the wire. The elongation can be seen microscopically, and is quite obvious in some alloys.

As recrystallization begins, new grains appear which are equiaxed, rather than elongated. The appearance of equiaxed grains is the basis for one of the traditional procedures for metallurgical examination of conductors that have been involved in building fires [2.5-2.7].

Experimental results with OFHC wire showed that the elongation of the grain structure was not very distinct, and in itself is not of much value to the military investigator.

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RECRYSTALLIZATION, Continued

Discussion (cont'd) The amount of recrystallization depends on the temperature and the length of time the conductor is exposed. The rate of recrystallization is governed by the same principles as a chemical reaction. As a general rule, a 10°C increase in temperature will be accompanied by a halving of the exposure time to achieve the same level of recrystallization.

Data	Conductor Type	Annealing Temperature
	OFHC	700 - 1200°F (370-650°C)
	HSCA	1000 - 1400°F (535-760°C)

Analysis Procedures for recrystallization analysis are given in Chapter 2, Section C.

Examples Testing on OFHC wire illustrates the recrystallization mechanism. Samples of new insulated wire were heated in an oven to produce the results shown on the next page.

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RECRYSTALLIZATION, Continued

Figure 2.3 Grain structure of normal OFHC wire (500X).

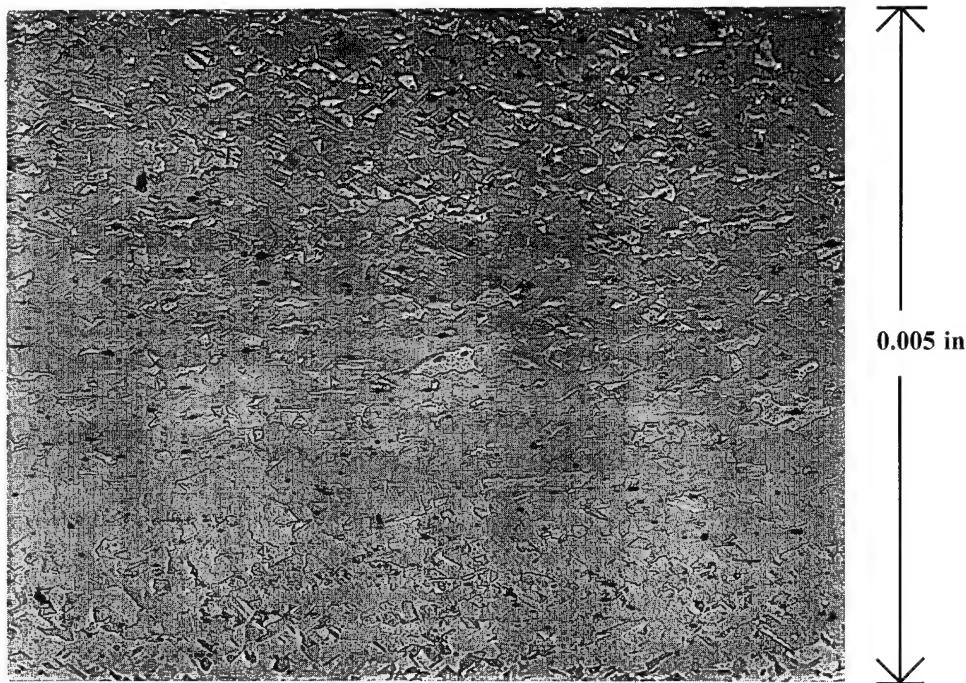
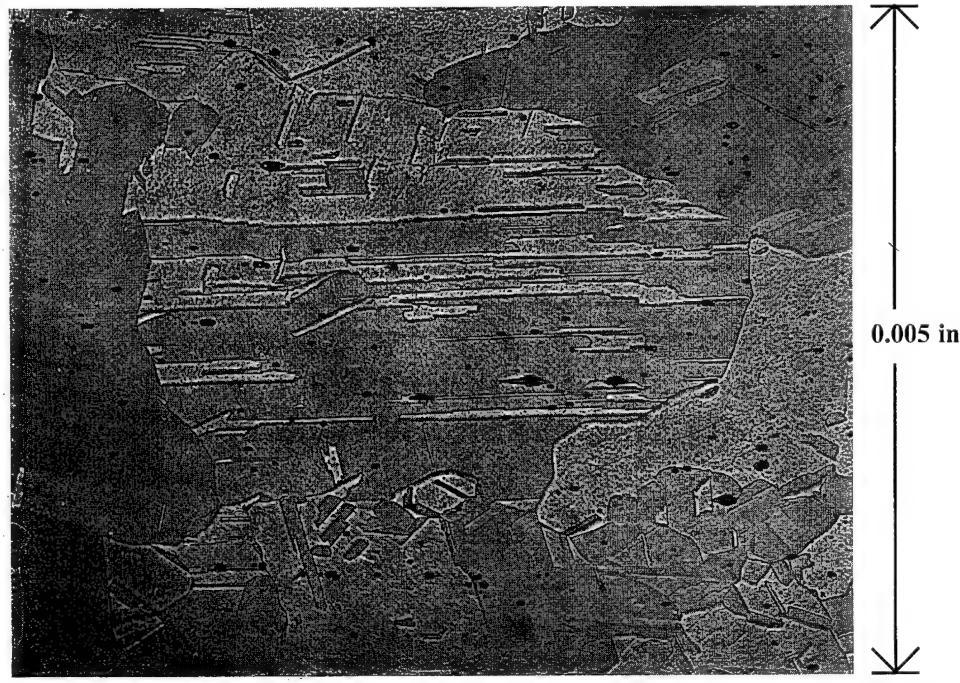


Figure 2.4 Grain structure of OFHC wire after five minutes at 600°C (500X).



BEADED WIRE ENDS

Observation	Extreme non-uniform heating results when wiring is involved in electrical arcing. The heating causes the copper to melt and form spherical globules, or beads, on the ends of wire strands. The bead shape is characteristic of arc phenomenon and is an indicator that temperatures well in excess of the melting point were achieved.
Cause	Beaded wire ends are an indicator of electrical arcing.
Mechanism	Electrical arcing frequently occurs when two conductors of opposite polarity come in contact or close proximity. Arcing from conductors to the aluminum airframe is also common since the airframe is generally at the ground potential of the electrical system. Intermittent contact occurs from chaffing and insulation breakdown. The heating is a result of the arc current and the voltage drop that occurs where the arc is established. The voltage-current product associated with the arc represents the thermal power available to cause conductor melting. For example, a 20 A short-circuit on a 28 V system will result in 560 Watts of thermal power. Most of this power will be dissipated in a relatively small area near the arc.
Precautions	Arc welding experience suggests that voltages at the arc will be between 10 and 35 V for currents up to several hundred amperes. The remaining voltage is dropped across the conductor resistance and the source impedance of the power system.
Discussion	Beaded wire ends sometime result from fire damage. Damage from maintained arcing is less likely on ac than on dc systems because of the opportunity for the arc to extinguish during the zero crossings of the ac waveform. Experience with commercial apparatus operated at 208 VAC/60 Hz suggests that sustained arcing below the trip level of overcurrent protection devices is unlikely. Wires in intermittent contact, or where significant conductive materials exist across a conducting path, may continue to arc without exceeding the trip levels of overcurrent devices. Arcing will be associated with non-uniform melting and loss of conductor material.

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BEADED WIRE ENDS, Continued

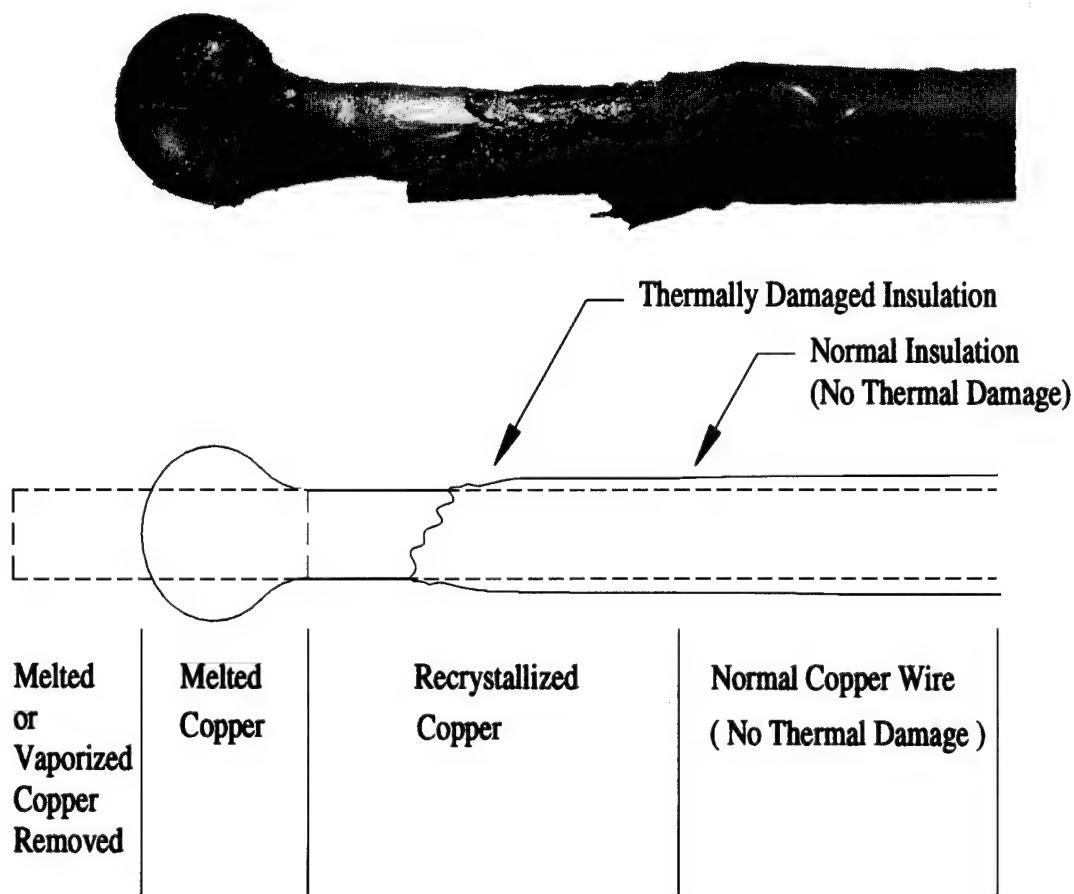
Discussion (cont'd) Recrystallization will tend to occur near the point of arcing and along the current-carrying portion of the conductor. The amount of recrystallization will depend on the current level and duration of the fault.

Beaded wire ends are a non-uniform characteristic.

Data The melting point of copper is 1981°F (1083° C).

Analysis Visual inspection of wire ends is generally sufficient to verify arcing.

Examples Figure 2.5 shows the appearance of a wire that was involved in arcing on a 28 Vdc system.



METAL TRANSFER

Observation	Metal transfer occurs in electrical arcs due to the melting of the constituent metals and their interaction with the arc plasma.
	Metal transfer between two distinctly different materials can be verified by SEM/EDS.
Cause	Metal transfer is an indicator of electrical arcing.
Mechanism	Arcing frequently occurs between conductors of different materials or between conductors and the aluminum airframe. Metal transfer generally, but not always, occurs between two conducting materials.
	Metal transfer occurs when an arc forms between two conductors with sufficiently high energy that one of the metal surfaces is heated to vaporization. At that temperature, ionized atoms leave the heated surface and are transported to the other side of the arc by the voltage drop across the arc. In some cases metal is transferred in droplets which are visible on adjacent surfaces.
Precautions	This test should always be done on a comparative basis using samples of the undamaged materials as a baseline. One reason for this precaution is that several aircraft aluminum alloys contain enough copper to be detected by EDS systems.
Discussion	This analysis requires that the suspect conductors be of different materials. Aluminum structural members and copper-based conductors are a typical example. In this case copper in the aluminum or aluminum in the copper conductor would be indicators that arcing had occurred.
	There must be enough damage to visually identify the arcing sites.
	The direction of transfer may depend on the size and polarity of the conductors.
	Metal transfer is generally associated with arcing and significant loss of conductor materials.
Data	No additional data.
Analysis	Verification of the metal transfer can be conducted with SEM/EDS. This analysis may be useful in supporting a failure hypothesis involving suspected arcing.

Continued on next page

METAL TRANSFER EXAMPLES, Continued

Figure 2.6 Experimental results of an arc between a copper conductor and a sample of 2024 aluminum are shown in the SEM photo of Figure 2.6. The figure shows spatter and oxidation on the aluminum sample.



Figure 2.7 Droplets of copper deposited on the aluminum is visible at higher magnifications in Figure 2.7.



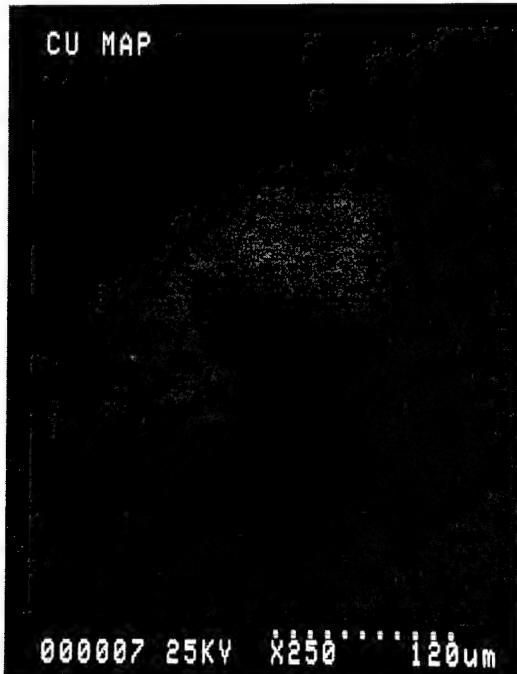
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METAL TRANSFER EXAMPLES, Continued

Figure 2.8 Backscatter images are very useful in this type of examination since they provide structural and elemental information in the image. Elements of higher atomic number (Z) appear brighter as shown in Figure 2.8, where the copper (Z=29) is plainly visible against the background of aluminum (Z=13).



Figure 2.9 Figure 2.9 shows an x-ray map of the same area and verifies that copper has been deposited on the aluminum.



CUP-AND-CONE FRACTURE

Observation A cup-and-cone fracture can occur when a ductile material undergoes tensile loading that exceeds its tensile strength.

Cause A cup-and-cone fracture surface is an indication of mechanical failure.

Mechanism High tensile stress on wire occurs frequently during mishaps. Initially, under high tensile stress the wire will elongate. The elongation is accompanied by a reduction in cross-sectional area called necking.

Once necking occurs, voids form in the center and are edged by radially forming cracks. The spreading cracks form a shear lip near the surface at a 45° angle. The characteristic cup consists of a flat center region with dimples and an outer 45° shear lip; the opposite fracture surface forms the cone.

Precautions Tensile failure may occur while the conductors are carrying load current. Fracture appearances under this condition have not been well characterized.

Discussion The motion of aircraft components during a mishap is extremely complex. Many types of force and effects occur which can cause mechanical failure in different conditions. The classical ductile failure shown here is just one type of mechanical failure that can occur.

Data The approximate breaking force of some stranded conductors is listed below for reference [2.8].

Gauge	Stranding	Approximate Breaking Force
8	133/29	480
10	137/26	295
12	19/25	172
14	19/27	108.5
16	19/29	68.7
18	19/30	53.8
20	19/32	34.4
22	19/34	21.3

Analysis Analysis is conducted by SEM examination of the fracture surface.

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CUP-AND-CONE FRACTURE EXAMPLES, Continued

Figure 2.10 Figure 2.10 shows the cup-and-cone fracture surface and elongation typically associated with mechanical failure of a copper conductor.

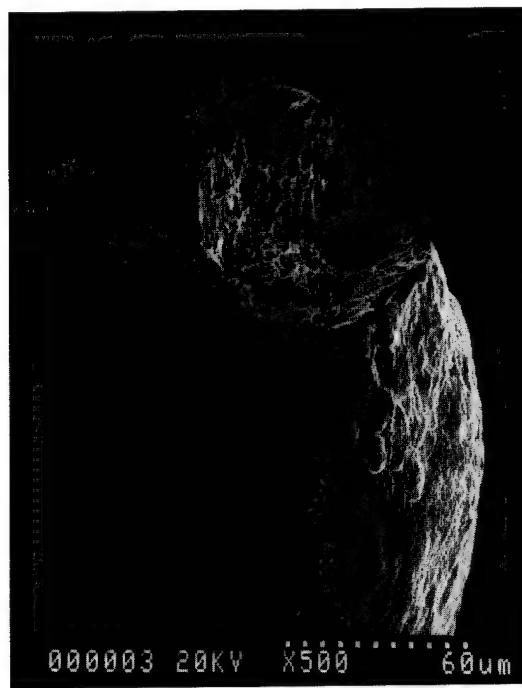
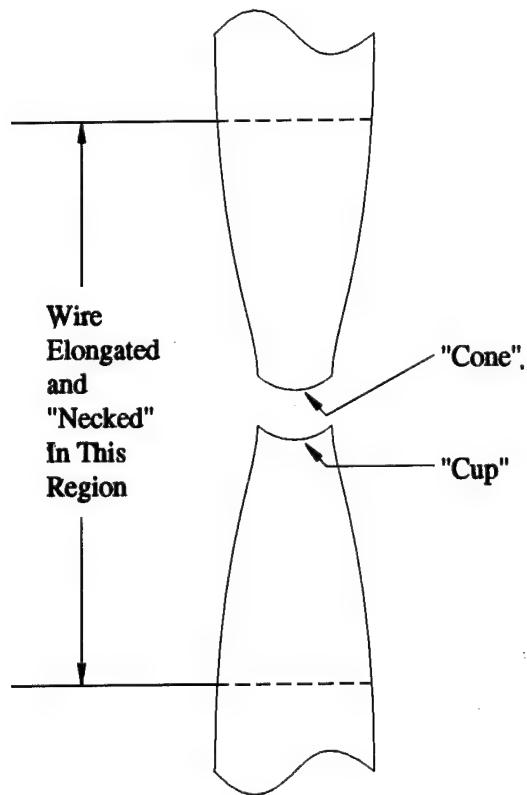


Figure 2.11



INSULATION FAILURE

Observation Insulation failure is the catastrophic electrical breakdown of the insulation material. It is usually attributed to poor arc-tracking resistance and is caused by carbonization of the insulation material.

The carbonized insulation is conductive and provides a current path between the conductor and other live electrical components.

Insulation failure may occur over time, or may happen very suddenly as when initiated by mechanical abrasion of the insulation material.

Flashover is the sudden catastrophic failure and carbonization of the insulation material.

Cause Insulation failure is an electrical failure condition, but may be initiated by mechanical abrasion or chafing.

Mechanism Arc-tracking resistance is a fundamental property related to insulation failure and flashover.

In the early stages of insulation breakdown, low current discharges occur between the conductor and other energized components. These may occur at pinhole flaws in the insulation or at sites where chemical contamination has compromised the insulation. Tracks develop along the discharge path on the surface of the insulation. The tracks are generally more conductive than the virgin insulation. The material is said to have poor arc-tracking resistance if these tracks carbonize quickly into significant conducting paths.

Poor arc-tracking resistance has been reported to be a property of highly phenylated polymers such as aromatic epoxies, phenolics, and polymers with the para-phenylene group in the polymer chain. Aromatic polyimide films have this structure and are susceptible to flashover [2.9].

At bends in the wire, radial cracks may develop from manufacturing defects or chafe damage and propagate completely through the insulation material to the conductor. The bare conductor is thereby exposed rather quickly, catastrophically accelerating the breakdown. Environmental factors can greatly accelerate insulation mechanical property degradation. Examples are sunlight (ultra-violet radiation), moisture, and various aircraft fluids.

Continued on next page

INSULATION FAILURE, Continued

Precautions	Insulation failures in Polyimide insulated wire are difficult to diagnose because of the rapid, catastrophic failures that can occur.
Discussion	The problem is especially severe in moist environments. Initially the conduction occurs in small, non-uniform areas which become carbonized quickly. Other materials such as polyethylene and polytetrafluoroethylene degrade into gaseous products rather than solid carbonized products. These materials apparently do not exhibit flashover in wet environments.
	Insulation failure is generally an initiating event and is accompanied by arcing.
Data	No additional data.
Analysis	SEM analysis may be conducted on polymeric insulation in an attempt to identify metallic contaminants or deposits from preliminary arc tracking events. However, the approach is of little practical use in mishap investigation because of the unlikelihood of finding a specific location on the wire where the events occurred.
	In specific cases it is possible to reconstruct the mishap scenario by building up a portion of a wire bundle in the laboratory. By energizing the bundle and mechanically damaging the insulation it is possible to confirm hypotheses about arc tracking as a failure mechanism in a specific mishap.
Examples	No pertinent examples.

THERMAL DAMAGE TO INSULATION

Observation Polymeric wire insulations are easily damaged at elevated temperatures. They also have poor thermal conductivity so that damage is usually restricted to portions of the insulation that are close to the heat source.

Cause Thermal damage is caused by exposure to any heat source and is not specific to one failure condition.

Specific characteristics will be discussed that may indicate which condition caused the damage.

Mechanism Polymeric materials undergo chemical breakdown at elevated temperatures. Although each material is different some common changes in properties are:

1. Gradual discoloration, usually darkening.
2. Loss of flexibility and cracking.
3. Loss of electrical resistance properties.

Precautions Severe thermal damage causes some insulation to crumble or "flake off" the conductor. Additional care is needed to preserve the insulation material for laboratory analysis.

Discussion The maximum temperature that the wire or insulation was exposed to is generally the most useful information for mishap investigation. Unfortunately thermal damage depends on the temperature and exposure time so that maximum temperature is difficult to judge from a visual examination of the insulation alone. Nonetheless it is customary to get some indication of temperatures that might have been attained by noting the damage relative to the known properties of the insulation material.

The location of the damage is sometimes more useful than the extent. A few notable cases are listed below.

Damage on inside surface of insulation. When the insulation is peeled away from the conductor the inside surface appears discolored while the outside surface does not. This suggests that the conductor itself was the heat source as in the case of electrical overcurrent.

Continued on next page

THERMAL DAMAGE TO INSULATION, Continued

Discussion (cont'd) *Damage on outside surface of insulation.* The insulation is damaged on the outside surface only. This suggests that an external heat source was involved.

Insulation resistance changes. Typical insulation resistances exceed 100 MΩ when measured between the outside surface of the insulation and the conductor under ideal conditions. After significant thermal damage, resistances below 1 MΩ can be measured. This may be used to verify the damage. Kapton is an example of a material that exhibits this behavior.

Glazing. Some materials become shiny or glazed when exposed to a radiant heat source. Again, Polyimide is an example.

Data Melting of polymeric insulation is a common indicator. Insulation made of thermoplastic polymers will exhibit melting before significant chemical breakdown occurs. The melting temperatures for some materials of this type are listed below and provide a rough guide during examination:

1. Polyethylene 212-300°F (100-150°C)
2. PVC 221°F (105°C)
3. Nylon 392-482°F (200-250°C)
4. PTFE 620°F (327°C)

Thermosetting polymers will not melt at elevated temperatures. The first signs of damage may be cracking or discoloration. Typical maximum service temperatures for some thermosetting materials are listed below:

1. Silicones 500°F (260°C)
2. Polyimides 500-600°F (260-315°C)

Carbonization of aromatic polyimide occurs in the range of 650°C.

Additional data and properties of polymers can be found in [2.10].

Analysis Insulation damage can be determined by visual inspection and by using a multimeter to determine insulation resistance.

Examples Thermal damage to insulation is shown in Figure 2.5.

Continued on next page

CONDUCTOR DISCOLORATION

Observation	Discoloration of the conductor is caused by thermal exposure and is a result of oxidation and absorption of coating materials into the copper.
Cause	Not specific.
Mechanism	Characteristic color changes have been noted on wires at slightly elevated temperatures, even before significant thermal damage occurs. Although the color changes themselves are not important, they can provide some useful clues to the investigator during initial visual examinations.
Precautions	A variety of chemical compounds are present in post-impact fire which can cause conductor discoloration. The examples below should be used as general points of reference only.
Discussion	No additional discussion.
Data	No additional data.
Analysis	Analysis of surface compound can be made by SEM/EDS in most cases.
Examples	<p>Some known color changes are listed below:</p> <ol style="list-style-type: none"> 1. Silver coated wire. Between 392 and 482°F (200 and 250°C) the silver and copper diffuse into each other. The wire loses its shiny appearance and takes on a dull brown color. 2. Tin coated wire. A similar mechanism occurs at lower temperatures, in the range of 302 to 338°F (150 to 170°C). 3. Brown, red and black copper oxides form on the surface of the conductor after the plating has disappeared. The color may depend on the thickness of the oxide layer. 4. Green copper-based compounds form when the base metal is exposed to moisture, water, and other liquids. This sometimes occurs when the copper is exposed to the elements, as a result of extreme thermal damage or arcing. 5. Silver coated wires frequently take on a dull yellow color at relatively low temperatures. This may be caused by the formation of sulfides or other compounds of silver. Fuel, hydraulic fluid and fire-fighting foam can cause a variety of compounds like this. Specific analysis, possibly with EDS, may be required.

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SECTION C

FAILURE ANALYSIS PROCEDURES

OVERVIEW

Introduction	This section guides the investigator through the process of determining the failure condition of wire under investigation.
Field Examination	Guidelines and precautions for field examination and handling are provided. Accurate documentation and minimum damage to the wiring are important factors.
Determine the Failure Condition	This process consists of two steps: <ol style="list-style-type: none">1. Reviewing all failure characteristics2. Relating identified failure characteristics to the most likely failure condition.
Laboratory Procedure	A specific laboratory procedure for examining the grain structure of copper wires is included in this section. SEM and EDS procedures are included elsewhere.

FIELD EXAMINATION

Introduction Field examination must be limited to what the investigator can see or measure with little analytical assistance. A magnifying glass and multimeter will be about the best tools for this work. The purpose of this examination is to identify any wiring that should be removed for laboratory analysis. There are three basic reasons why wiring can become interesting during an investigation:

- it was the ignition source for a fire
- it contributed to the failure of significant on board systems
- it provides information about possible mishap scenarios

Once a specific subsystem has been identified, the investigator may look for *any* non-uniform damage including:

- insulation damage or discoloration
- conductor melting
- beaded wire ends
- chaffing

Documentation The most important activity is to record precisely where the wiring was situated before removing it from the aircraft. Hand sketches of the area and photographic records are recommended. A list of suggested information to obtain for each sample of wire to be removed is presented in Table 2.5.

When a wire is cut for removal, both sides of each cut should be tagged and labeled with a unique identification number. The number should be referenced in sketches and included in photographs where possible.

Wire Removal The investigator should attempt to remove the largest section of wire practical. This provides the laboratory analysts with useful areas of undamaged wire for comparison purposes. If possible bundles or individual conductors should be removed in their entirety end-to-end.

Specifics If wiring failures are suspected at the point of connection to a piece of equipment, the equipment should be removed with the wire. Care should be exercised in removing the equipment especially when the interconnection itself is in question. The effective resistance of corroded, loose, or partially welded connections can be altered dramatically by small movements.

When arcing is suspected other nearby segments of wire or airframe material should be removed in addition to the wiring in question. This will allow the material in the opposing surfaces to be analyzed by EDS to verify materials transferred during the arcing. Samples for arc material analysis should always be included with undamaged areas for comparative analysis.

DETERMINING THE FAILURE CONDITION

Introduction Wire damage is a complex process. It is generally not possible to associate one failure characteristic to one failure condition. For example, recrystallization is associated with external thermal damage and overcurrent.

Procedure The failure characteristics must be identified first. Table 2.6 is a checklist of those characteristics and can be used during the examination process.

Once the failure characteristics have been identified the failure condition can be assessed by using Table 2.7.

Discussion It is helpful, and sometimes absolutely necessary, to examine adjacent wires to form a conclusion.

There will be some cases for which no specific condition can be determined.

There will be many cases where more than one condition was at work.

Precaution **Although the tables suggest that there is a "yes or no" quality to the data this is not the case. The best conclusion an investigator can achieve is a determination that one condition is the "most likely" to have caused the damage to the wire.**

FAILURE CHARACTERISTIC CHECKLIST

Table 2.6 Failure Characteristic Checklist.

CHARACTERISTIC	YES	NO	COMMENT
RECRYSTALLIZATION			
Uniform			
Non-Uniform			
BEADED WIRE ENDS			
Single Conductor			
Multiple Conductors			
METAL TRANSFER			
Conductor Deposits - EDS			
Structure Deposits - EDS			
CUP-AND-CONE FRACTURE SURFACES			
Single Strands/Wire			
Multiple Strands/Wire			
INSULATION FAILURE			
Carbonized Insulation Present			
Polyimide Insulation			
Chafing			
THERMAL DAMAGE			
External Heat Source Present			
Discoloration - Outside of Insulation			
Discoloration - Inside of Insulation			
Condition			
Temperature Rating for Decomposition or Melting			
Decomposition Apparent			
Electrical Resistance Change			
CONDUCTOR DISCOLORATION			
External Heat Source			
Conductor Heat Source			
Wire Coating			
Approximate Temperature for Discoloration			
Uniform			
Non-Uniform			

DETERMINING THE FAILURE CONDITION OF WIRE

Table 2.7 Determining the Failure Condition of Wire.

CONDITION	YES	NO
Electrical Overcurrent		
Recrystallization		
Discoloration of conductor		
Discoloration on inside surface of insulation		
Uniform damage		
Electrical Arcing		
Beaded wire ends		
Material transfer		
Nonuniform damage		
Insulation Failure		
Chafing		
Carbonized insulation		
Nonuniform damage		
Mechanical Failure		
Cup/cone fracture surface		
Elongation of wire end		
External Thermal Damage		
Insulation damaged on outside vs. inside		
Recrystallization		
Nonuniform damage		
Insulation resistance changes		

SAMPLE PREPARATION: GRAIN STRUCTURE

Introduction Sample preparation consists of four basic steps which are outlined below.

1. Sectioning
2. Mounting
3. Grinding
4. Polishing

The parameters and materials for automatic polishing equipment are provided below [2.11]. Most of this information pertains to manual preparation as well. The principles of metallography and sample preparation methods are covered in [2.12].

Sectioning Al_2O_3 Cutoff Wheel/Coolant.

Mounting Bakelite, Epoxide or Castable Mounting Media.

Grinding Table 2.8

SiC Grit Size	Time (secs)	Wheel Speed (rpm)	Pressure (psi)
240	60	300	40
600	60	300	40

Polishing Table 2.9

SiC Grit Size	Time (secs)	Wheel Speed (rpm)	Pressure (psi)
1 micron diamond compound/red felt/oil	180	250	30
Ferric oxide slurry/Lecloth	60	150	20

Continued on next page

SAMPLE PREPARATION: GRAIN STRUCTURE, Continued

Remarks	The Ferric Oxide final polish is recommended for microscopic examination in the as-polished condition; however, it leaves a passive film which is inert to etching. A few turns on an alumina polishing cloth will remove the passivity for etching purposes. Gamma alumina (0.05 μ) can be used as the final polishing medium. The addition of a few drops of a solution composed of 50 ml NH ₄ OH and 5 ml H ₂ O ₂ will facilitate polishing.
Etchants	50 ml ammonium hydroxide (NA ₄ OH), 5 ml hydrogen peroxide (30%) H ₂ O ₂ - Immerse - NOTE: If etchant is too fast, add 50 ml H ₂ O. To differentiate between cuprous oxide and copper sulfide inclusions, examine in the as-polished condition under polarized light. Cuprous oxide will be red, copper sulfide will remain dark. Both are medium gray with brightfield illumination.

SECTION D

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2.14 Corrosion of Silver-plated Copper Conductors. D.B. Dunn, et al. European Space Agency Journal Vol. 8, No. 3. 1984.

2.15 SEM Examination of an Overheated Aluminum Wired Electrical Receptacle. Proceedings of the 34th Annual Electron Microscopy Society of America. 1976. pp. 454-455.

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CHAPTER 3

CIRCUIT BREAKERS

OVERVIEW

Introduction Circuit breakers perform two roles in aircraft electrical systems. Their primary purpose is to provide overcurrent protection for the aircraft wiring. Their second function is to turn off power in electric circuits that do not contain any other switching mechanisms.

Observing the ON/OFF state of aircraft circuit breakers after a mishap can help determine the state of the aircraft's system prior to impact. Sometimes the information provided is inaccurate because circuit breaker position may change during impact.

Circuit breakers can be the cause of a mishap. They can open at less than rated current or fail to open under short-circuit conditions. These failures can be caused by a variety of mechanical and electrical failures that make aircraft systems lose power or overheat.

Contents This chapter is divided into four sections.

Section	Title	Page
A	Background	111
B	Failure Characteristics	121
C	Failure Analysis Procedures	141
D	References	151

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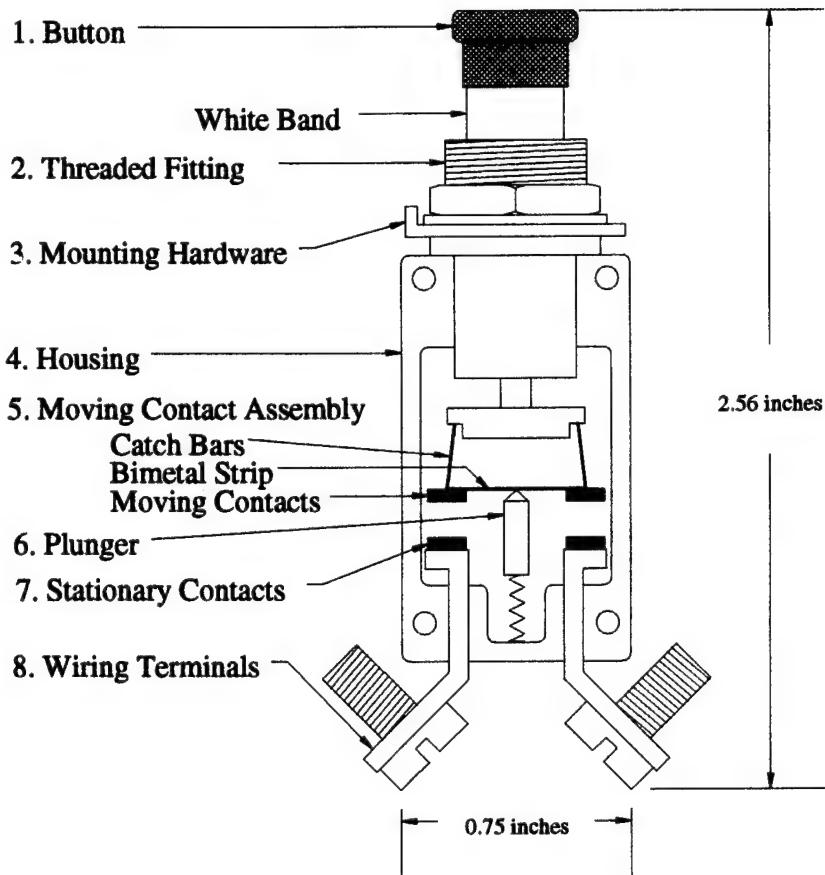
SECTION A

BACKGROUND

CONSTRUCTION

General The construction of thermal circuit breakers for aircraft depends on the manufacturer, rating, and application. The mechanical structures have changed over many years; therefore, age is also a factor.

Figure 3.1 The construction of one type of aircraft circuit breaker is shown in Figure 3.1. It is shown in the open circuit position.



Button The button is the manual operating means and its position indicates the state of the circuit breaker. Pushing the button closes the circuit and latches the button mechanism. The button can be pulled out to open the circuit.

The button shaft has a white band which, when visible, indicates that the circuit breaker is open.

Threaded Fitting A threaded fitting is provided for panel mounting.

Continued on next page

CONSTRUCTION, Continued

Mounting Hardware	A nut and lockwasher are used to attach the circuit breaker to a mounting panel. A keyway washer is used to align the circuit breaker in the panel and prevent rotation after installation.
Housing	A molded insulating housing provides mechanical support for mounting, contains the electrical contacts, and provides environmental protection for the internal components.
Moving Contact Assembly	<p>The moving contact assembly has three parts:</p> <ul style="list-style-type: none">• two metal catch bars• a central bimetal strip• two moving contacts <p>It is formed as one piece and is the central element in the operation of the circuit breaker.</p>
Plunger	A spring-loaded plunger is used to push the moving contact assembly to its extended position when the circuit breaker is opened.
Stationary Contacts	Stationary contacts are attached to the metal bus bars of the wiring terminals.
Wiring Terminals	Screw-type wiring terminals are provided for the electrical connections. A label on the housing identifies one terminal as the "line" side of the breaker.
Materials	<p>Some requirements for circuit breaker materials are found in MIL-5809 [3.1].</p> <p>Conducting elements are mostly silver-plated copper, brass, or copper-bearing alloys. Sometimes silver wire is used for connections between internal components.</p> <p>Housings and buttons are usually made of thermosetting polymers. Glass-reinforced polyester and glass-filled polycarbonate are also found in some designs.</p> <p>Bimetal strips are a laminate of two metals with different coefficients of thermal expansion (CTE). The high CTE side is usually an iron alloy containing nickel and chrome. The low CTE side is usually an iron-nickel alloy. A typical commercial material has 22 Ni, 3 Cr, 75 Fe on the high CTE side and 36 Ni, 64 Fe on the low CTE side [3.2].</p>

CONSTRUCTION EXAMPLES

Figure 3.2 Photo of a 10 A circuit breaker made by Klixon Division of Texas Instruments shown in the closed position. Magnification: about 1X.

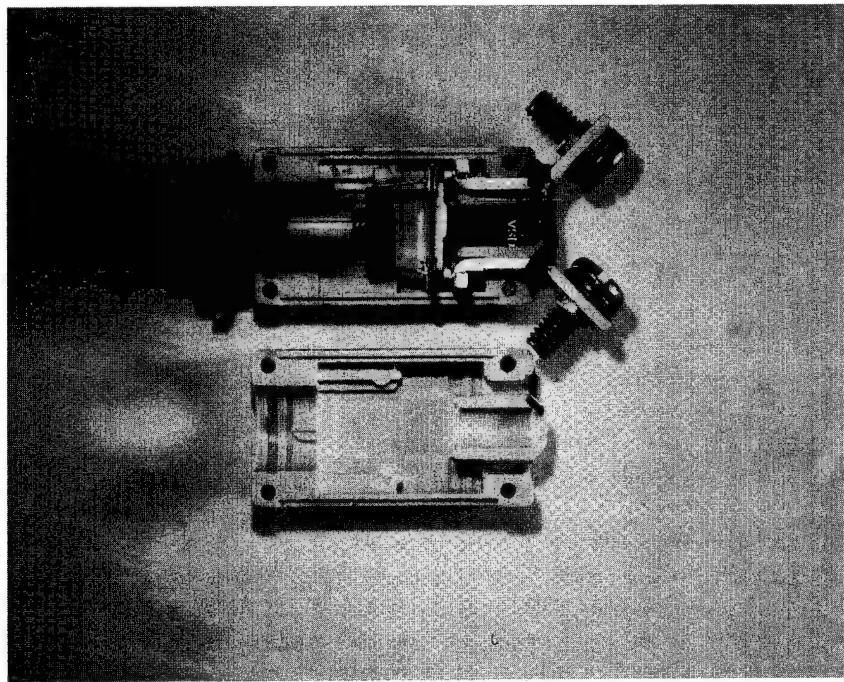
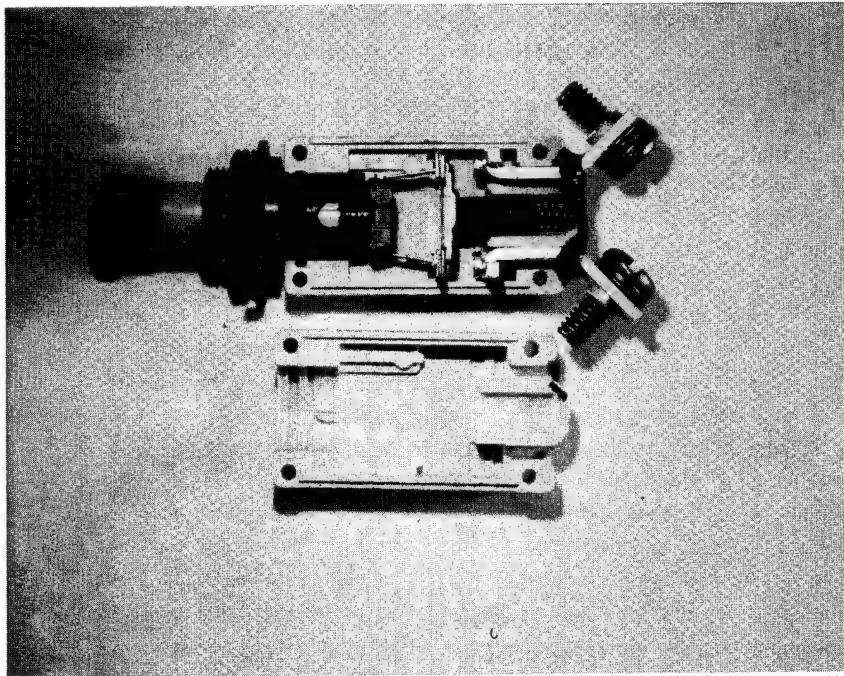


Figure 3.3 Photo of a 10 A circuit breaker made by Klixon Division of Texas Instruments shown in the opened position. Magnification: about 1X.



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CONSTRUCTION EXAMPLES, Continued

Figure 3.4 Photo of a 10 A circuit breaker made by Mechanical Products shown in the opened position. Magnification: about 1X.

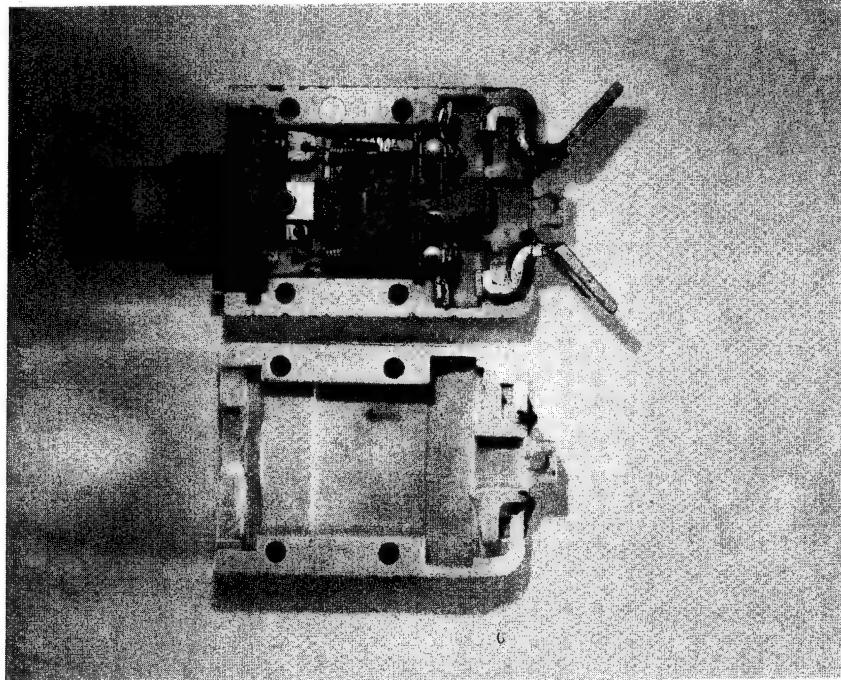
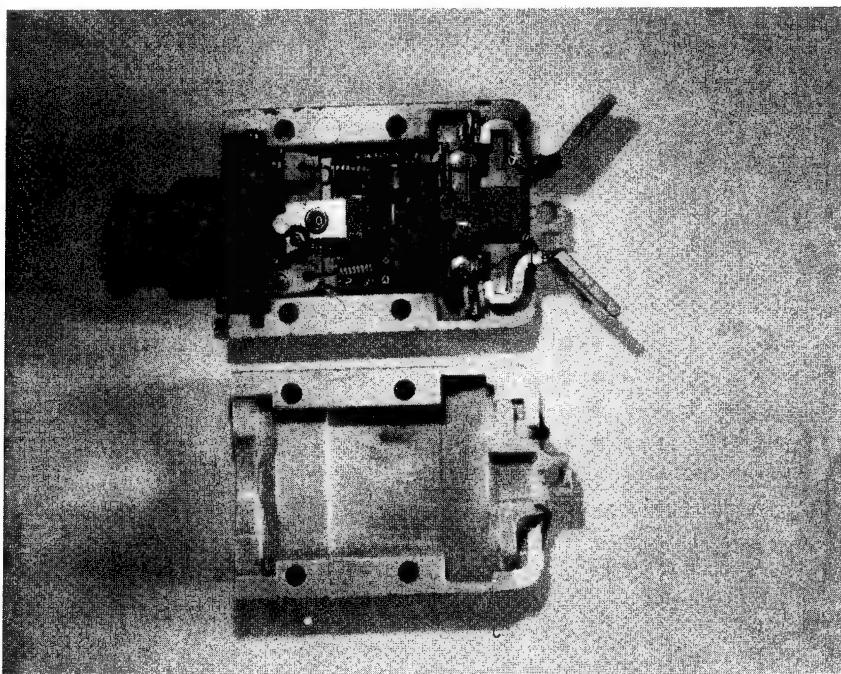


Figure 3.5 Photo of a 10 A circuit breaker made by Mechanical Products shown in the closed position. Magnification: about 1X.



OPERATION

Manual Operation

The button allows the circuit breaker to be operated manually. The position of the button also indicates the state of the circuit breaker. Pushing the button closes the circuit and latches the button mechanism. The button can be pulled out to open the circuit.

The button shaft has a white band which is visible only when the button is in the extended (open) position. This is an additional indicator that the circuit breaker is open.

Overcurrent Trip

If an overcurrent trip condition occurs when the breaker is in the closed position, the electrical contacts open and the button pops out. The circuit breaker must be manually reset after tripping. This is done by pushing in the button until it latches.

Trip Mechanism

The moving contact assembly is an essential element in the overcurrent trip mechanism of the circuit breaker. The assembly contains the moving contacts which mate with the stationary contacts when the circuit breaker is closed.

Load current flows between the moving contacts through a bimetal strip in the center of the moving contact assembly. Two metal catch bars extend from the bimetal strip and rest against the button assembly.

As the temperature of the bimetal strip rises, the higher CTE metal component expands at a greater rate than the lower CTE component. This causes the strip to bend, separating the ends of the catch bars. When the catch bars separate far enough with an overcurrent load, a spring-loaded mechanism in the button assembly is released. The entire button assembly moves toward the front of the circuit breaker and away from the stationary contacts as the button pops out. Many circuit breakers have an adjustable screw for calibrating the overload trip current.

A spring-loaded plunger forces the sliding contact frame away from the stationary contacts and opens the circuit. The plunger pushes the sliding contact frame against a stop near the button assembly. The circuit breaker cannot be re-closed until the bimetal strip and catch bars return to their normal condition.

Continued on next page

OPERATION, Continued

Trip Time Characteristics The most important electrical data for the mishap investigator is the time required for the circuit breaker to interrupt an overcurrent condition. This data is found in the MIL Standard covering the particular style of circuit breaker.

Required operating time ranges for one type of circuit breaker are shown in Table 3.1 [3.3]. Notice that the interruption times are longer for lower currents which provides inrush current capability for motor starting, transformer inrush, etc. This is accomplished with the natural time-overcurrent response of the bimetal strip. Higher currents will distort the bimetal strip and trip the circuit breaker faster than low currents.

Table 3.1 Overcurrent Trip Time Requirements. (From MS 22073).

TRIP TIMES AT 25° C	
Percent of Rated Current	Trip Time
115	Must hold: 1 hour minimum
150	Must trip: 1 hour maximum
200	2 to 20 seconds
500	0.16 to 2.0 seconds
1000	0.046 to 0.8 seconds
TRIP LIMITS AT -55° C	
135	Must hold: 1 hour minimum
180	Must trip: 1 hour maximum
TRIP LIMITS AT 71° C	
90	Must hold: 1 hour minimum
130	Must trip: 1 hour maximum

CONTACTS AND CONTACT MATERIALS

Composition Circuit Breaker contacts are made either of pure silver or silver alloys. Alloying materials include cadmium oxide (CdO), tin oxide (SnO) and tungsten (W). The most common alloy is silver-cadmium oxide. This alloy is usually 10 to 15 percent CdO by weight and made by sintering powdered mixtures of the components. The alloy can be made using either cadmium oxide or cadmium. Pre-oxidized contacts are made with CdO. Post-oxidized contacts are made using cadmium and then oxidizing them after the sintering process. Post-oxidized contacts may contain some residual unoxidized cadmium.

The addition of cadmium oxide to silver reduces the susceptibility of the contacts to welding, improves erosion characteristics, and increases current handling capability [3.4].

Fabrication The contacts are made separately, then brazed or soldered onto contact assemblies. Common base materials for the contact assemblies are copper, brass and phosphor-bronze.

Structure Most circuit breaker contacts are made in one of two basic structures. Some contacts are button shaped like the one shown in the Figure 3.6. Rectangular bar shapes are also used. Both shapes can be arranged so that wiping action takes place as the contacts mate.

Figure 3.6 Contact from a 10 A circuit breaker. Magnification: 25X.



STANDARDS AND MANUFACTURERS

MIL-C-5809 The general requirements for aircraft circuit breakers are found in military specification MIL-C-5809 [3.1]. The specification covers thermal (Type I) and magnetic (Type II) circuit breakers. The circuit breakers are rated from 28 Vdc to 208 Vac and 0.5 to 100 A. Requirements for the construction, performance and testing of circuit breakers are also included.

Table 3.2 Detailed data on specific types of circuit breakers from MIL-C-5809.

MIL STD	OPERATOR	RATING	PHASE	TYPE
MS3320	Push-Pull	1/2 to 20 A	1	I
MS26574	Push-Pull	1/2 to 20 A	1	I
MS22073	Push-Pull	1/2 to 20 A	1	I
MS22074	Push-Pull	1/2 to 5 A	1	I
MS14105	Push-Pull	25 to 35 A	1	I
MS24510	Push-Pull	5 to 15 A	1	I
MS25244	Push-Pull	5 to 50 A	1	I
MS25361	Push-Pull	50 to 100 A	1	I
MS14154	Push-Pull	1 to 20 A	3	I
MS14153	Push-Pull	1 to 35 A	3	I
MS21984	Push-Pull	5 to 60 A	3	I
MS25304	Toggle	0.1 to 50 A	1	II
MS24509	Toggle	5 to 15 A	1	I
MS25337	Toggle	5 to 50 A	1	unspecified

Continued on next page

STANDARDS AND MANUFACTURERS, Continued

Manufacturers Two manufacturers of circuit breakers for military use are listed below:

- Mechanical Products
Division of Aiken Industries
Jackson, Michigan
- Klixon
Division of Texas Instruments
Attleboro, Massachusetts

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SECTION B

FAILURE CHARACTERISTICS

OVERVIEW

Introduction Aircraft circuit breaker operating mechanisms are reasonably reliable and fail-safe in their design. In addition, the condition of the operating mechanism is relatively unaffected by the electrical parameters of the load circuit. In contrast, the contacts can show signs of wear, arcing, and other features which relate to the number, type, and current level of electrical operations. The contact surfaces, therefore, contain information about the condition of the electrical equipment connected to the circuit breaker. For this reason, they will be the focus of this section.

Contents This section covers the following characteristics:

- Contact Wear
- Material Transfer
- Overcurrent
- Contact Welding
- Contamination

CONTACT WEAR

Observation	Contact wear is the result of arcing and/or mechanical abrasion. It results in a visible change in the appearance of the contacts which can provide clues about the number of operations and types of loading conditions.
Cause	Excessive contact wear suggests repeated overcurrent tripping and may indicate abnormal electrical conditions in the loads supplied by the circuit breaker.
Mechanism	Mechanical operation below the current rating does not cause significant contact wear.
Precautions	Contact wear resulting from dc loads differs dramatically from that observed as a result of ac service. DC inductive circuits will cause more severe wear on contacts than dc resistive circuits.
Discussion	The ac aging results shown in Fig 3.7 and 3.8 were conducted at 60 Hz. Arcing between contacts as they begin to open under load is the primary wear mechanism. The arc usually extinguishes when the sinusoidal current waveform passes through zero. At higher power frequencies the time required to reach a zero crossing and the average arcing time are both reduced. As a result, wear is much less severe at 400 Hz than at 60 Hz.
Data	Usually circuit breaker contacts may be operated up to 5 or 10 thousand cycles without showing abnormal wear. Contact wear at 120 Vac is much more severe than dc operation.
Analysis	Contact wear can be examined by optical microscopy or SEM.
Examples	The photographs on the following pages of this article show new circuit breakers aged in an apparatus which mechanically opened and closed them using their operating button. The circuit breakers were each operated in 28 Vdc or 120 Vac 60 Hz circuits, with current applied and resistive loads selected to draw the rated circuit breaker current.

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CONTACT WEAR EXAMPLES

Figure 3.7 Contact from a new 10 A circuit breaker. Magnification: 25X.

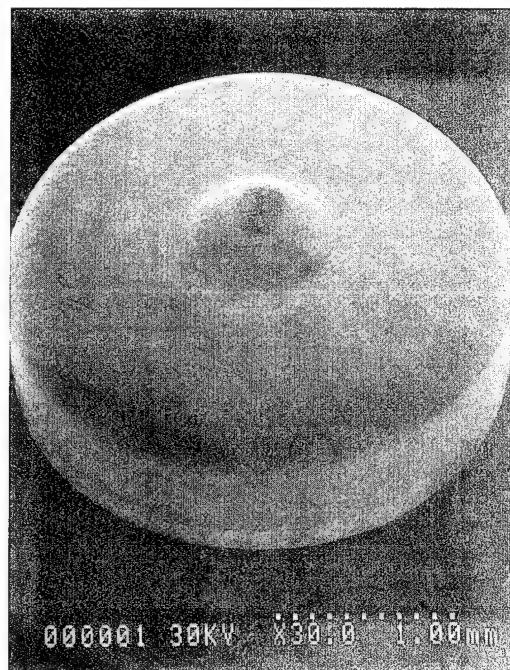
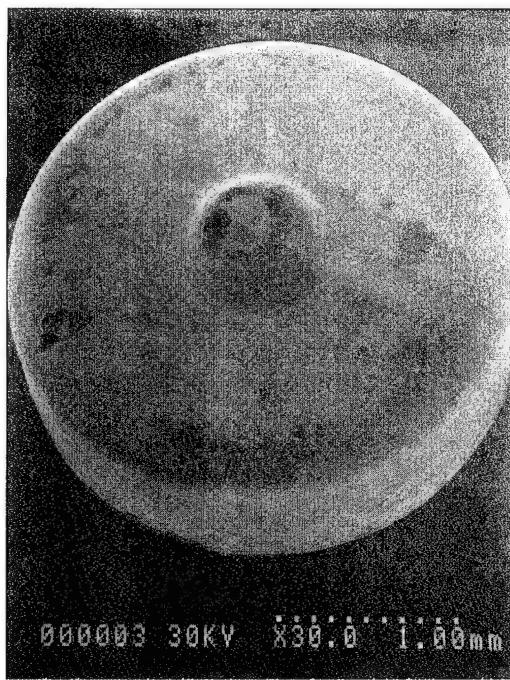


Figure 3.8 Contact from a 10 A circuit breaker cycled 10,000 times with no load. Magnification: 30X.



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CONTACT WEAR EXAMPLES, Continued

Figure 3.9 Contact from a 10 A circuit breaker cycled 10,000 times at rated dc load current at 28 Vdc. Magnification: 30X.

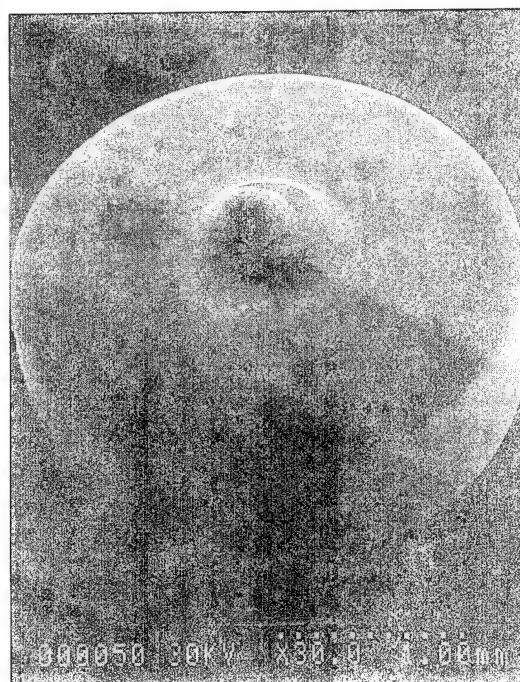
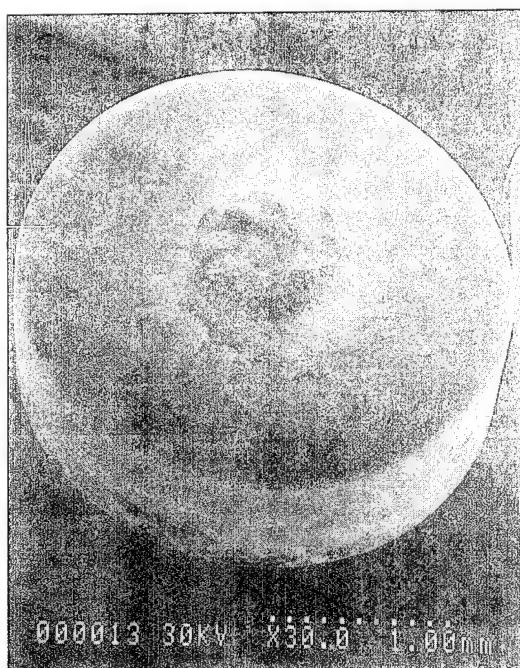


Figure 3.10 Contact from a 10 A circuit breaker cycled 20,000 times at rated dc load current at 28 Vdc. Magnification: 30X.



Continued on next page

CONTACT WEAR EXAMPLES, Continued

Figure 3.11 Contact from a 10 A circuit breaker cycled 10,000 times at rated ac load current at 120 Vac / 60 Hz. Magnification: 30X.

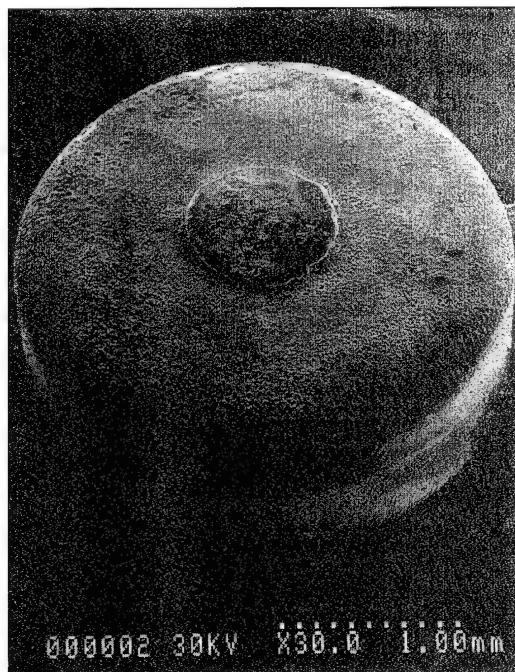
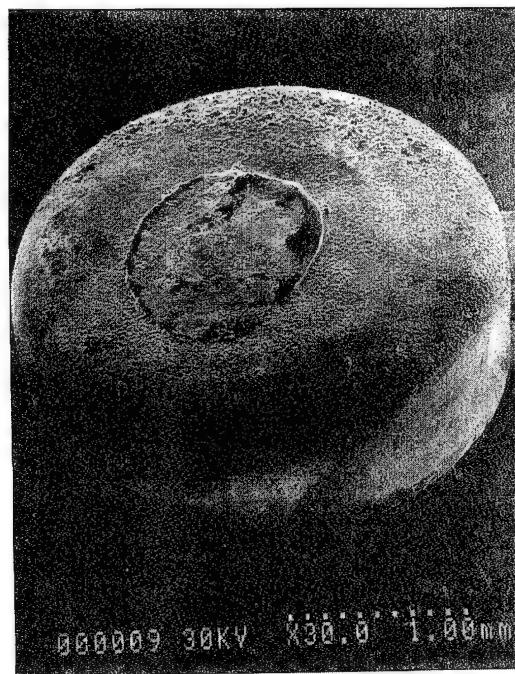


Figure 3.12 Contact from a 10 A circuit breaker cycled 20,000 times at rated ac load current at 120 Vac / 60 Hz. Magnification: 30X.



MATERIAL TRANSFER

Observation	Material is transferred between mating contacts of a circuit breaker, due to the arcing that occurs as the contacts part under load.
	Their appearance can provide clues about the direction of current flow in dc circuits, and information about certain types of abnormal conditions.
Cause	Material transfer is caused by repetitive operation of breaker contacts in dc circuits.
Mechanism	<p>As the circuit breaker contacts begin to part under load the current is confined to a reduced area at the mating surface between the contacts. The resistance of the contact material and the high current density cause local heating which melts the contacts as they begin to separate. At the same time, the circuit inductance attempts to maintain the current by forcing an additional voltage to be developed across the contacts. An arc is created as a result.</p> <p>As the arc begins to bridge the gap between the contacts, electrons flow from the cathode to anode. Electrons leaving the cathode absorb energy from the surface as they enter the arc. This results in a slight cooling effect at the cathode. There is still a net heating effect in the contacts because of the I^2R loss in the bulk material of the contacts.</p> <p>Heating occurs at the other end of the arc as electrons deposit energy into the anode. This adds to the I^2R loss at the anode. The net effect of the electron energy in the arc makes the positive contact hotter than the negative contact [3.5].</p>
Precautions	Material transfer is generally in the direction of conventional current flow. The terms cathode and anode as used above relate to conventional current flow and must not be confused with markings on electric circuit components. It is also possible for current to flow backwards through the circuit breakers during abnormal conditions, including any damage that may occur to the circuits as a result of a mishap. This can happen in breakup and ground impact. These situations must not be overlooked when examining circuit breaker contacts.
	The appearance of material transfer may be obscured when the circuit breaker interrupts high dc currents.
Discussion	Material transfer is from the hotter contact to the cooler and thus occurs in the direction of conventional current flow (in the opposite direction of electron current flow).
Data	In dc circuits the anode will be marked with depleted areas called craters. The cathode will be marked with mounds or cone-shaped deposits called pips.

Continued on next page

MATERIAL TRANSFER EXAMPLES

Analysis Contact wear can be examined by optical microscopy or SEM.

Figure 3.13 Positive contact (anode) from a 10 A circuit breaker cycled 10,000 times with a dc resistive load at rated current. Notice crater formation in center of contact. Magnification: 30X.

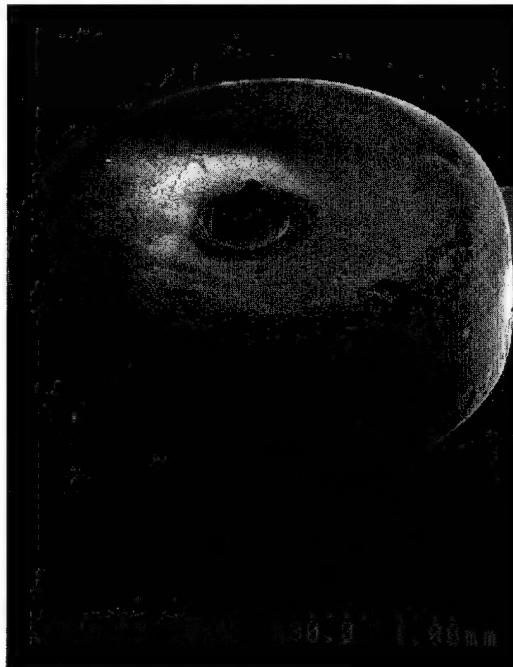
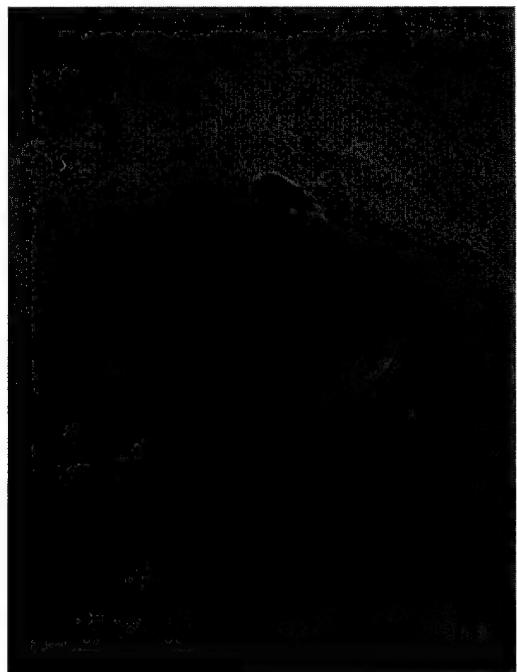


Figure 3.14 Close up of crater formation on positive contact. Magnification: 100X.



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MATERIAL TRANSFER EXAMPLES, Continued

Figure 3.15 Negative contact (cathode) from a 10 A circuit breaker cycled 10,000 times with a dc resistive load at rated current. Notice pip in center of contact. Magnification: 30X.

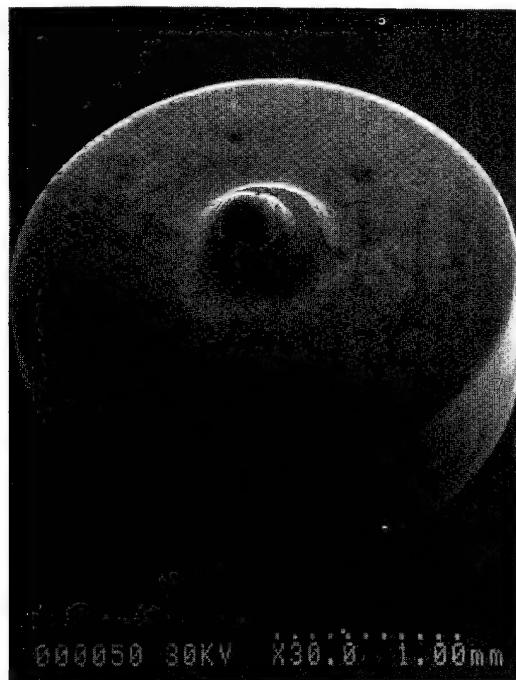
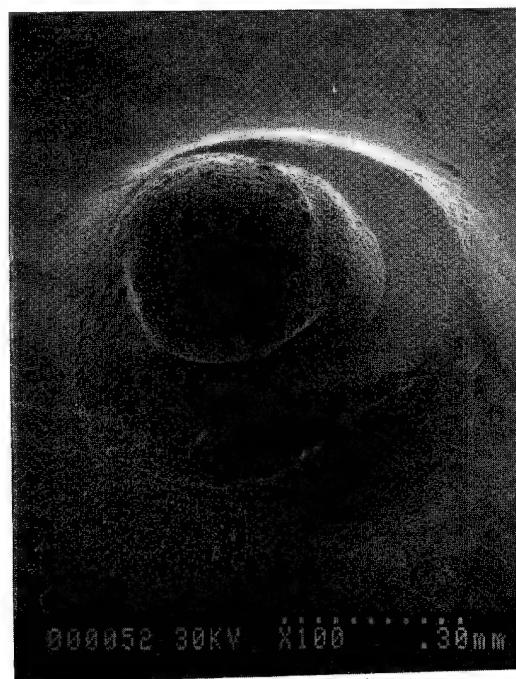


Figure 3.16 Close up of pip on negative contact. Magnification: 100X.



OVERCURRENT

Observation	Circuit breaker contacts can be damaged by the interruption of currents in excess of ten times their rating. Their appearance may indicate that overcurrent interruption may have occurred and provide clues about abnormal electrical events.
Cause	Overcurrent damage can be caused by electrical failure of equipment, wiring shorts, and accidental electrical connections. Any of these events may occur during a mishap.
Mechanism	Electrical system component and wiring failures can lead to overcurrent conditions which cause circuit breaker tripping. The basic mechanism resulting from overcurrent conditions is prolonged arcing. This causes melting and redistribution of the contact materials. Contacts take on a "splattered" appearance.
Precaution	The investigator should always examine all the contacts from a circuit breaker to increase the confidence level of any findings. Mating contacts should be properly identified as to their location and purpose in the existing circuitry.
Discussion	Most circuit breakers will have completed a number of normal cycles prior to an overcurrent event. This aging effect will mask the damage caused by more recent overcurrent events and complicate the investigation. The investigator may need to perform some test to recreate the damage patterns of the circuit breaker in question, when aging is an issue.
Data	Severe arcing due to overcurrent events causes melting of the contact materials. Silver melts at 960°C (1760°F) and cadmium oxide decomposes at 1010°C (1850°F).
Analysis	Contact wear can be examined by optical microscopy or SEM. A redistribution of the Ag and CdO components may be detected with SEM/EDS.

Continued on next page

OVERCURRENT, Continued

Examples The photographs on the following pages are intended to provide some guidance in gauging the severity of overcurrent conditions. The examples were made with new circuit breakers using a 28 Vdc source and resistive loads. The circuit was energized with the circuit breaker closed, forcing the circuit breaker to interrupt the load current.

Inductive loads will cause more damage to circuit breaker contacts than resistive loads because of the stored energy available to maintain the arc as the contacts part.

Continued on next page

OVERCURRENT EXAMPLES

Figure 3.17 Positive contact (anode) from a 10 A aircraft circuit breaker after one interruption at 100 Adc. The duration of the current interruption was about 75 ms. Magnification: 35X.



Figure 3.18 Positive contact (anode) from 10 A aircraft circuit breaker after 10 interruptions at 100 Adc. The duration of the current interruption was about 75 ms. Magnification: 35X.



Continued on next page

OVERCURRENT EXAMPLES, Continued

Figure 3.19 Positive contact (anode) from a 10 A aircraft circuit breaker after one interruption at 1000 Adc. The duration of the current interruption was about 2 ms. Magnification: 35X.

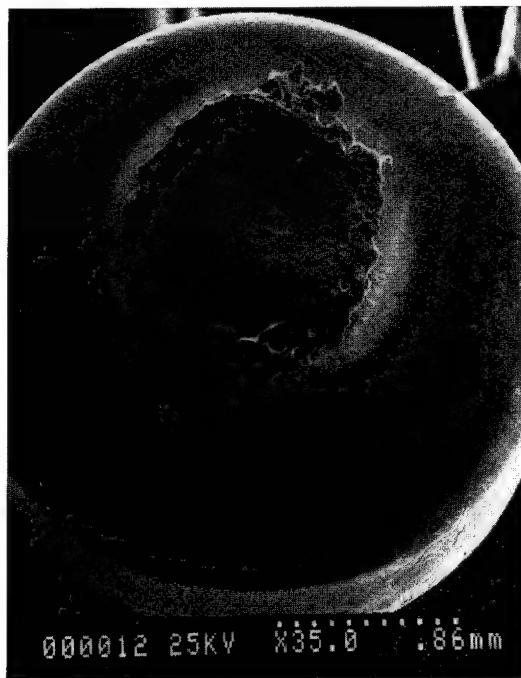
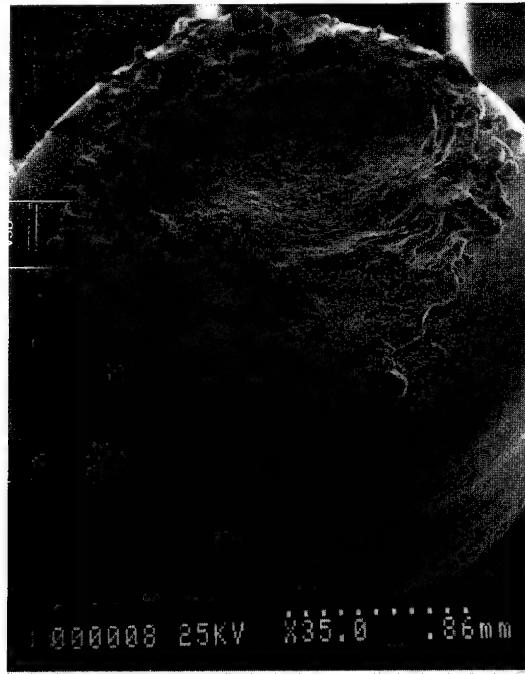


Figure 3.20 Positive contact (anode) from 10 A aircraft circuit breaker after 10 interruptions at 1000 Adc. The duration of the current interruption was about 2 ms. Magnification: 35X.



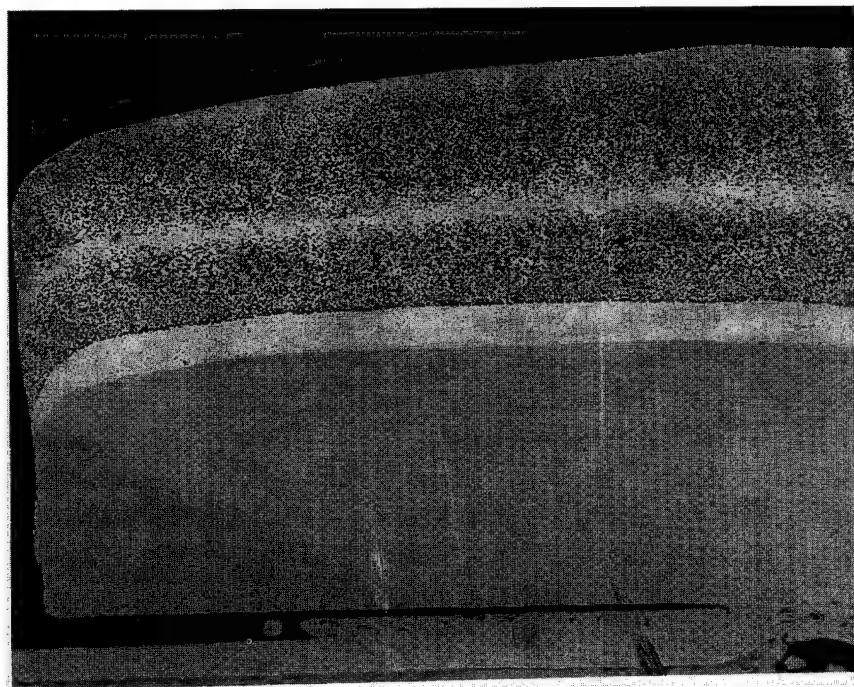
CONTACT WELDING

Observation	Circuit breaker contacts occasionally weld together in the closed position. The condition is usually associated with a massive internal failure of the circuit breaker.
Cause	A contact weld failure may indicate problems with the circuit breaker, or unusual surge currents in the load.
Mechanism	A condition associated with contact welding is migration of the Ag and CdO components at the surface of the contacts. In dc circuits the positive contacts will become CdO rich over time while the negative contacts will be Ag rich [3.6]. Mechanical misalignment may also be a cause of welding. This causes a reduction in the mating area of the contacts. A current surge melts the contacts in the reduced mating area and the contact material solidifies before the circuit breaker can open. Failure occurs during a subsequent overcurrent condition or equipment failure.
Precaution	Metal migration can cause mating contacts to lock together mechanically and behave like welded contacts. Welded contacts will be quite brittle and may be damaged by the standard mounting procedures for metallographic specimen preparation. X-ray and visual verification of welding should be conducted before removing the contacts from the circuit breaker.
Discussion	The addition of CdO was adopted to reduce the susceptibility to welding. Tungsten is also used for this purpose.
Data	No additional data.
Analysis	Migration of the contact material alloys can be examined with a metallurgical microscope. X-ray radiography may also be conducted to verify that welding has occurred.
Examples	No examples of welded contacts are presented here.
	Figure 3.21 shows the normal appearance of the AgCdO alloy on the top surface of the circuit breaker contacts.

Continued on next page

CONTACT WELDING EXAMPLES

Figure 3.21 Metallurgical microscope photograph of a circuit breaker contact. The speckled appearance on the upper half of the contact indicates the AgCdO alloy. Magnification: about 100X.



CONTAMINATION

Observation	Contaminants inside the circuit breaker can cause the contacts to have a high resistance in the closed state. Contaminants can also cause arcing between the contacts, and can foul the mechanical operation of the breaker. Contaminants can be observed visually, or with the SEM. Identification may be done with the SEM or with infrared spectrography.
Cause	Contaminants can enter the circuit breaker housing if the housing is damaged or improperly sealed. Contaminants can also be trapped inside during manufacturing. Contamination can also be caused by severe arcing which can burn and dislodge housing materials.
Mechanism	Foreign material may be sealed inside the circuit breaker. Pieces of metal, plastic, clothing fibers and other organic material may be trapped in the breaker during manufacturing. While initially harmless these materials may eventually relocate and interfere with the contacts. If conductive, the foreign matter may cause an electrical short between the contacts when the breaker appears open. If non-conductive, the material may prevent proper electrical contact when the breaker is closed. The materials may also prevent or impede the proper mechanical operation of the circuit breaker. Environmental contaminants, such as dirt, moisture, and cleaning agents may enter the circuit breaker if the housing is not sealed properly, or if it is damaged after installation. These materials will degrade the insulating properties of the housing. When the contacts open under load the contaminated surfaces become an alternate path for arcing, as the load current is being interrupted. The arcing can burn off small fragments of the housing material and vaporize volatile compounds in insulating materials. This, in turn, introduces additional loose solid particles and coats the contacts with condensed volatile insulating compounds.
Precautions	Moisture, fibers and small particles can be lost when the circuit breaker housing is opened. Disassembly and examination must be conducted with care to avoid losing this evidence.
Discussion	Infrared (IR) spectrographic analysis can be used to identify specific materials. In one case, clothing fibers were found in the circuit breaker. IR analysis showed that the fibers were an ester-based polyacrylonitrile, which is an acrylic fiber used in clothing.

Continued on next page

CONTAMINATION, Continued

Data	Tungsten-oxide, can form in high temperature and high humidity environments. Silver tungstate may also be found on Tungsten alloy contacts.
Analysis	Visual examination can uncover signs of arcing. SEM and x-ray analysis can verify contaminants on or near the contacts themselves. Infrared spectrographic analysis may be used to identify complex organic materials.

Continued on next page

CONTAMINATION EXAMPLE

Figure 3.22 A circuit breaker contact which has been contaminated by the housing material - a glass-filled polyester. Since the material is non-conductive, it charges up in the SEM and appears bright white as in the photo below. Magnification: 30X.

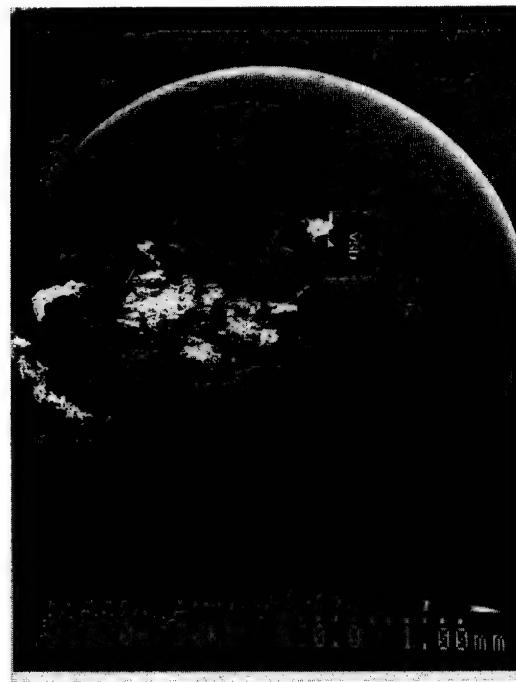
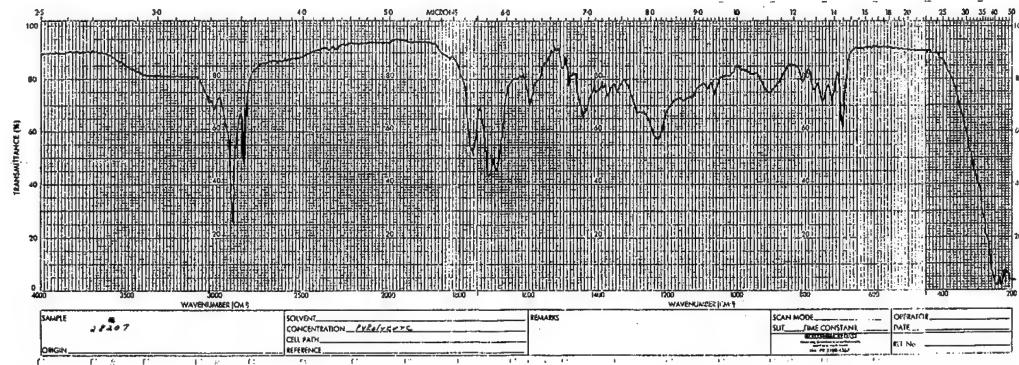


Figure 3.23 A sample of infrared spectrographic analysis data identifying the acrylic fibers found inside a switch.



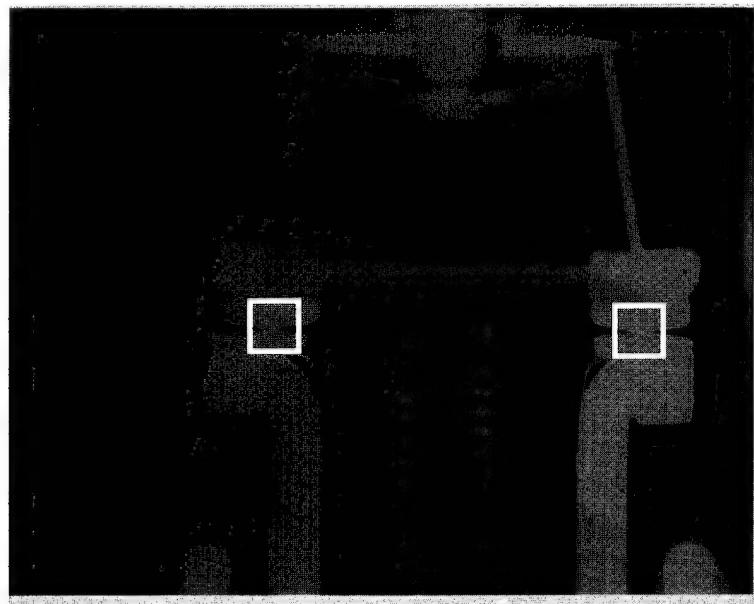
MECHANICAL FAILURE

Observation	Although electrical failures are more common, mechanical failures of circuit breakers can occur. The failures can be from abnormalities in the manufacturing process, wear, corrosion, or contamination obstructing the mechanism.
Cause	Mechanical failure can be caused by corrosion of the internal mechanism of a circuit breaker. Internal contamination and manufacturing defects could also cause a mechanical failure.
Mechanism	Mechanical failures can be caused by failure of internal components, or foreign materials trapped in the housing. Internal component failures can result from changes in the construction materials of the circuit breaker. This sometimes happens when alterations are made to the manufacturing process.
Precaution	Mechanical component failure is not common, and should be verified by testing additional circuit breakers from the same manufacturing lot.
Discussion	A fractured reset button spring is one example of mechanical failure which has been observed. The pieces of the spring fell into the contacts, causing an internal short.
Data	No additional data.
Analysis	X-ray examination of the circuit breaker before disassembly may reveal possible mechanical problems. Radiography is one of the best diagnostic tools, since most circuit breakers will not work properly after disassembly. Real time microfocus x-ray is the ideal tool for this type of investigation.

Continued on next page

MECHANICAL FAILURE EXAMPLES

Figure 3.24 An X-ray radiograph of a circuit breaker operating mechanism. The point of contact between stationary and moving contacts is visible in the photograph and is shown by the boxes. Magnification: about 5X.



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SECTION C

FAILURE ANALYSIS PROCEDURES

OVERVIEW

Introduction	This section outlines procedures for field and laboratory examination of circuit breakers, and includes some specific analysis procedures.
Field Examination	Guidelines and precautions for field examination and handling are provided. Accurate documentation and minimum damage to the circuit breaker are important factors. A suggested list of data describing each circuit breaker selected for laboratory analysis is included.
Laboratory Procedures	An outline of the basic steps for laboratory examination is provided.
Analysis Procedures	The following analysis procedures are covered in this section: <ul style="list-style-type: none">• Contact Resistance• Insulation Resistance• X-Ray Radiography• Contact Sample Preparation

FIELD EXAMINATION

Introduction Field examination must be limited to what the investigator can see or measure with little analytical assistance. A multimeter is the best field tool for this work. The purpose of this examination is to identify any circuit breakers that should be removed for laboratory analysis.

There are three basic reasons why a circuit breaker can become important during an investigation:

- it was the ignition source of a fire
- it contributed to the failure of an on-board system
- it provides information about possible mishap scenarios.

Documentation Recording the function, rating and location of the circuit breaker is essential. Hand sketches and photographic records are recommended. Include both the front and rear of the panel in the sketches and photographs. This is especially true if the circuit breaker will be removed from the panel at the site.

A sample circuit breaker identification form is presented in Table 3.3. Be sure to record this information and tag each circuit breaker with an ID number when it is removed.

Removal Mark the wires to the circuit breaker with tape or wire markers and cut them several inches away from the breaker. The wires should be marked so that conductors to each terminal of the circuit breaker can be identified later.

Without changing the position of the circuit breaker, carefully loosen the nut on the front panel and remove the breaker from the panel. Re-assemble mounting hardware so that it remains with the circuit breaker.

Observation Circuit breaker buttons should be examined carefully during investigations of mishaps involving fires. The white band on the button may become covered with soot if the circuit breaker tripped before the fire. This may provide a clue as to the sequence of electrical events.

Precaution Aircraft circuit breakers have what is called a "trip-free" feature. This insures that the breaker will trip in response to an overload, even if the button is jammed in the closed position. This provides a fail-safe mechanism which allows the breaker to perform its function regardless of external forces. Therefore, even though a breaker may appear to be closed, it may have tripped.

It should also be noted that a breaker may trip as a result of the shock of an impact. Therefore the appearance may not indicate an overload.

Continued on next page

FIELD EXAMINATION, Continued

Table 3.3 Sample Circuit Breaker Identification Form Sample.

Aircraft	<i>F111</i>
Sample ID#	<i>CB 101</i>
Date of Mishap	<i>04/03/90</i>
Date Removed from Site	<i>04/03/90</i>
Breaker Type	<i>Push-Pull 1 Phase</i>
Breaker Rating	<i>10 A</i>
Location Found At Site	<i>in cockpit panel</i>
Function Labeled on Aircraft Panel	<i>LH Fuel Pump</i>
Location in Panel	<i>Middle of top row</i>
Panel or Instrument Name	<i>Center panel between seats</i>
Manufacturer's Name	<i>Mechanical Products</i>
Manufacturer's Part Number	<i>700-801-705-10</i>
MS Number	<i>MS25244</i>
Date Code	<i>7024</i>
Wiring Configuration: Line Side	<i>2 #16 White</i>
Wiring Configuration: Load Side	<i>1 #18 White</i>
Position of Button	<i>Closed</i>
Contact or Leakage Resistance	<i>Closed, <0.1 Ω</i>
Measuring Instrument	<i>Fluke 75 DMM</i>
Comments	<i>Button Melted</i>

**REMINDER: DO NOT CHANGE POSITION OF CIRCUIT BREAKER
BUTTON IN FIELD**

LABORATORY EXAMINATION

Introduction The general steps for laboratory examination are outlined below. The detailed procedures for specific analyses are included in this section.

Procedure Outline This list should be considered as a guide only. Only the appropriate steps should be performed, depending on the circuit breaker's condition.

1. Verify that all necessary identifying data have been recorded.
2. Make a preliminary measurement of the contact resistance to verify the electrical state of the circuit breaker.
3. Obtain an X-ray radiograph to confirm the internal state of the circuit breaker.
4. Measure the contact resistance after radiography has been completed to verify that the circuit breaker has not been inadvertently operated.
5. Perform contact resistance measurements in accordance with MIL-C-5809.
6. Perform insulation resistance measurements in accordance with MIL-C-5809.

Inspection Most circuit breaker housings consist of two halves joined together with rivets. Terminal assemblies are sometimes cemented together with an epoxy-like material which may also be used to seal the two halves of the housing. The exterior of the terminals may be covered with an elastomeric potting compound. The steps below outline the procedure for disassembly and inspection of the internal components.

1. Remove potting compound using a razor blade or sharp knife. Examine the terminal area for arcing or leakage. Check for loose screws, corrosion, improperly terminated wires, etc.
2. Drill out the heads of the rivets and remove the rivets from the housing.
3. Separate the housing halves with a sharp knife.
4. Photograph the internal components of the circuit breaker.

The steps below are another procedure for inspecting the internal components. This procedure allows for operation of the circuit breaker and measurement of the temperature of the contacts and other components.

1. Grind away an area of the housing at the contact level until the plastic housing is very thin.
2. Cut out the remaining plastic to form a window exposing the contacts.

Continued on next page

LABORATORY EXAMINATION, Continued

Contact Examination A through visual examination may be made when the circuit breaker has been disassembled. The condition of the contacts may then be determined by optical microscopy and the SEM where applicable. The overall steps are outlined below:

1. Visually examine the contacts and internal surfaces of the circuit breaker. Note any pertinent damage or discoloration of components, and make a sketch or photograph the details before removing the contacts.
2. Label the contact assemblies before removing them from the circuit breaker. Identify any specific terminology used in the labeling on a sketch or photograph. Military circuit breakers are marked on the line side, and this notation can be useful in identifying contacts and test results. Also note if the contacts are moving or stationary.
3. Optical and SEM micrographs similar to those shown in this chapter can reveal information about the condition of the circuit breaker.
4. Cross sectioning of the contacts and metallurgical examination can sometimes provide clues about the composition and possible causes of welding.

CONTACT RESISTANCE

Measurement Preliminary contact resistance measurements can be made in the field or laboratory using a conventional multimeter. This will confirm that the electrical and mechanical states of the circuit breaker are consistent.

Contact resistance measurements will be possible only on circuit breakers that are found in the closed position. Do not close the circuit breaker in the field to make the measurement, since this could cause internal damage and alter the condition of the circuit breaker.

Formal measurements should be made in accordance with MIL-C-5809, for consistency. The procedure passes current through the circuit breaker and measures the voltage drop across the contacts. The current should be 200 mA, or 1/2 the current rating of the circuit breaker, whichever is less.

Typical Values MIL-C-5809 does not specify the contact resistance necessary for qualification. Instead, it refers to the change in contact resistance from the original condition of the circuit breaker after certain environmental and storage tests. The change should not be more than 250 mV above the original value. This corresponds to a resistance increase of no more than 1.25Ω .

The contact resistance of a new 10 A circuit breaker should be less than 0.1Ω . Contact resistance can also be related to the power dissipation in the breaker while operating at rated current. MIL-C-5809 requires that this power not exceed 15 watts.

Precaution Caution should be taken in handling the circuit breaker if the contacts are apparently closed but have a high resistance. The concern here is to prevent any accidental movement of the contacts which could obliterate the cause of the high resistance and restore electrical continuity.

INSULATION RESISTANCE

Measurement Preliminary insulation resistance measurements can be made in the field with a multimeter, if the circuit breaker is found in the open position. Do not open a closed circuit breaker in the field to make the measurement. The opening operation could cause internal damage and change its condition. These measurements are useful to have on record as part of the documentation with a circuit breaker that is removed for laboratory analysis. The measurements may provide an indication of insulation degradation if contamination, especially moisture, has been a problem.

Formal measurements should be made in accordance with MIL-C-5809 for consistency. The procedure is to apply 500 Vdc to the breaker and measure the leakage current. The test has two parts:

1. The voltage is applied between the line and load terminals with the breaker in the open position.
2. The voltage is applied between the terminals and parts normally grounded such as the mounting hardware and frame. This part is done with the breaker both opened and closed. In the field, take only data with the circuit breaker in the position in which it was found.

Typical Values

The insulation resistance of a new 10 A circuit breaker should be more than $20\text{ M}\Omega$ when measured with an multimeter.

MIL-C-5809 requires the insulation resistance to be greater than $100\text{ M}\Omega$.

The leakage current of a new 10 A circuit breaker at 1500 Vac, 60 Hz should be less than $500\text{ }\mu\text{A}$.

Precaution

If the insulation resistance measured below $1\text{ M}\Omega$ with a multimeter, it may be an indication of severe contamination and/or moisture trapped in the circuit breaker. Since moisture could evaporate during shipment from the mishap site, the laboratory should be notified of this condition.

DIELECTRIC WITHSTAND VOLTAGE

Measurement The procedure from MIL-C-5809 involves applying a high voltage to the circuit breaker terminals to verify that no damage results. The test has two parts:

1. The voltage is applied between the line and load terminals with the breaker opened.
2. The voltage is applied between the terminals and parts normally grounded, such as the mounting hardware and frame.

The voltage is applied at 60 Hz ac and must be equal to twice the rated voltage of the circuit breaker plus 1000 V, but not less than 1500 Vac. For the test to be successful, there should be no evidence of breakdown, flashover, or leakage current in excess of 1.0 mA.

Typical Value The leakage current of a new 10 A breaker at 1500 Vac, 60 Hz should be less than 500 μ A.

Precautions These tests are generally considered destructive, and should be used only on non-critical samples. In particular, the test can break down insulating contaminants on contacts thereby obliterating any useful information about the condition of the circuit breaker.

This test should only be conducted on circuit breakers that have successfully passed the insulation resistance test. The dielectric withstand test is usually reserved for production samples.

X-RAY RADIOGRAPHY

Examination X-ray examination of circuit breakers can be a valuable procedure for determining the internal condition of the circuit breaker before opening the housing. Most circuit breakers have plastic housings which are reasonably transparent to X-rays. The internal metal components will be rendered clearly visible in the radiographs.

Microfocus X-ray equipment is the best choice for this type of examination, because of the ability to view the small internal components of the circuit breaker with a high resolution. [3.7, 3.8]

Conventional x-ray radiographs can be photographed and enlarged using a light table and camera stand. Radiographs may also be placed in a photographic enlarger to magnify details.

Typical Result A typical X-ray radiograph is shown in Figure 3.24.

Precaution X-ray radiography should be performed before the circuit breaker is disassembled or operated to verify the condition and position of internal components.

CONTACT PREPARATION FOR METALLURGICAL EXAMINATION

Introduction Sample preparation consists of five basic steps which are outlined below. The parameters and materials for automatic polishing equipment are provided below [3.9]. Most of this information pertains to manual preparation as well. The principles of metallography and sample preparation methods are covered in [3.10].

Sectioning Al_2O_3 Cutoff Wheel/Coolant.

Mounting Bakelite, Epoxide or Castable Media.

Grinding Table 3.4

SiC Grit Size	Time (secs)	Wheel Speed (rpm)	Pressure (psi)
240	40	300	25
600	60	300	25

Polishing Table 3.5.

SiC Grit Size	Time (secs)	Wheel Speed (rpm)	Pressure (psi)
3 micron diamond compound/silk cloth/extender (oil)	60	250	25
1 micron diamond compound/red felt cloth/extender (oil)	120	250	30
0.05 micron gamma alumina/Imperial cloth/water	30	150	20

Etchants 50 ml H_2O_2 , 25 ml NH_4OH , 3ml H_2O_2 - Immerse.

Cleaning Rinse and dry sample before mounting.

Rinse with soap and water between grit sizes to avoid contamination with a larger size grit.

SECTION D

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CHAPTER 4

CONNECTORS

OVERVIEW

Introduction Aircraft, including military aircraft, have complex electrical and electronic systems. They encompass numerous components, interconnected with miles of wiring. Connectors, therefore, are considered fundamental to the installation, operation, and maintenance of these systems. They facilitate the insertion and removal of instruments and instrument panel assemblies, electrical motors, wiring harnesses, generators, batteries, relays, sensors, and many other components.

Connectors aid in the transfer of ac and dc current from power supplies to equipment, low voltage logic signals, and RF for radio transmitters and receivers.

Connectors do not contain any inherent information about the status of the equipment to which they are connected. The primary interest in connector failures is their potential causal role in a mishap. The construction of connectors and their failures in commercial aircraft are covered in [4.1].

In this chapter we will consider the crimped and soldered connections to external wiring as part of the connector.

Types of Connectors

There are many different connector styles and types for various applications, including rack and panel connectors, printed-wiring, coaxial, and circular connectors. The circular connector is one of the most common configurations used in aircraft, and is the basis for many of the discussions in this chapter.

Contents

This chapter is divided into four sections.

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SECTION A

BACKGROUND

Overview

Introduction This section covers the basic construction and materials used in aircraft connectors.

Contents This section is divided into four articles:

- Construction
- Types of Connectors
- Materials
- Military Standards

CONSTRUCTION

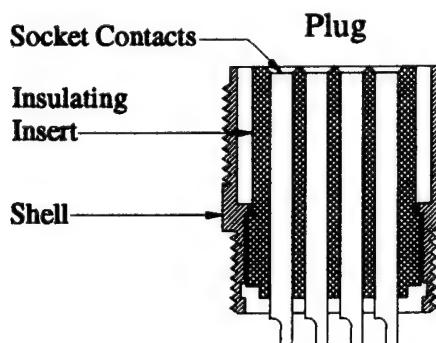
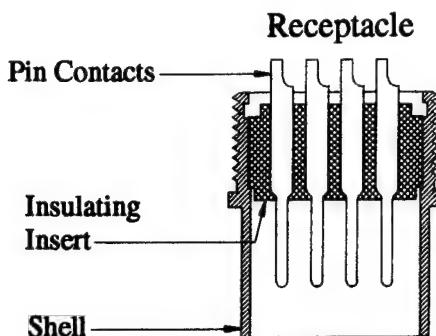
General

Connector construction depends mostly on the application. For example, connectors used in severe environments will have additional components to seal and protect the contacts. Each application has different requirements, resulting in a variety of design, materials, and mechanical configurations.

Figure 4.1 shows the simplified construction of a circular connector.

Figure 4.1

Simplified construction of a circular connector. The drawing is shown as a cross-section to illustrate the internal parts. The receptacle has the (male) contact pins and is usually mounted on the equipment. The plug has (female) socket pins and is usually mounted on the end of the wiring harness.



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CONSTRUCTION, Continued

Contacts The electrical connection between the mating parts of the connector is generally made using a pin and socket configuration. Contact pins in one half of the connector slide into contact sockets in the mating half. The contact socket usually has some type of spring device which keeps the mating parts in intimate contact.

Wires are connected to the contacts by crimping or soldering. Contacts can be molded into the insulator, or be inserted after the wires are connected. Contacts are made from a base metal with a relatively thin protective plating.

Base metal: provides strength, current carrying capacity and the spring characteristic necessary for proper retention. Typical base material are beryllium-copper, phosphor-bronze, spring brass, and low-leaded brass.

Protective plating: reduces the contact resistance and prevents corrosion. Gold is the most commonly used material. A minimum thickness of 50 microinches for the plating is generally required. The protective plating is plated over a thin barrier layer of nickel which is deposited on the base metal. Tin may be used as a plating material in some applications.

Insulating Insert The insert is the primary insulating component of the connector. It has three main functions:

- it provides insulation between the connector pins
- it insulates the pins from the metal shell
- it provides mechanical support for the pins

The insert material is crucial to the effectiveness of the connector in a particular application because it provides both mechanical strength and electrical insulation. Thermosetting plastics are typically used for this application.

Shell Most connector shells are made of aluminum or aluminum alloys. Hermetic connectors have steel shells. Finishes include: Nickel, Cadmium plating over Nickel, hard anodizing and Zinc Chromate. Some shells are made of a plastic material with a metal plating. The plating is usually nickel.

Continued on next page

CONSTRUCTION, Continued

Other Components Most connectors have additional hardware which are not shown in Figure 4.1. Some of these items are listed below:

1. **Grommet:** slides over the ends of the contact pins to seal the connector and protect the pins. Silicone and neoprene are commonly used materials.
2. **Follower:** compresses and retains the grommet. Nylon or other plastic materials are used for this purpose.
3. **Retaining Nut:** couples follower and insert to shell. Aluminum is usually used with aluminum shell connectors.
4. **Snap rings:** used to hold inserts and other parts in the connector shell. These are usually steel.
5. **Lockwasher, sleeves, and other springs:** used for a variety of mechanical functions. Steel, beryllium copper, and bronze are commonly used materials.
6. **EMI Shielding:** provided by an additional spring arrangement on the inside of the plug, or by a conductive polymeric gasket.

TYPES OF CONNECTORS

Circular Connectors Circular connectors have the most efficient shape for general military applications. In addition, there are a large number of accessories available in this configuration for mounting, sealing and protecting the conductors. Circular connectors are used over a wide range of applications, atmospheric pressure, and temperatures. Details of a common circular connector in widespread use on military aircraft is covered by MIL-C-38999 [4.2].

Rack and Panel Rack and panel connectors are usually used on removable equipment. One half of the connector is mounted on the rear of the equipment, and the mating half is mounted in the rack. When the unit is slid into the rack, locating pins insure proper alignment of the mating halves of the connector. Jackscrews are usually used to force the unit into final mounted position, and secure the engagement of the connectors. Rack and panel connectors are usually rectangular, or variations of rectangular shapes to prevent improper insertion. One aspect of rack and panel connectors is that neither half can be seen when engaging, due to their location at the back of the equipment.

Printed Circuit Connectors Connectors that mount directly on printed circuit boards fall into three categories:

1. Backplane connectors are used on main or motherboards. They accept the card edges of individual printed circuit boards which engage the backplane. Input/output connectors which provide external connections may also be mounted directly on the backplane.

2. Printed circuit boards are usually interconnected with ribbon cable. This type of cable is usually terminated in PC-type connectors having two rows of pins on 0.1 inch centers. This configuration complies with MIL-C-83503.

3. Small removable components are often directly attached to connectors which are soldered on the PC board. These include the following types and their numerous variants.

- DIP dual in-line package
- PGA pin grid array
- LCC leadless chip carriers

Continued on next page

TYPES OF CONNECTORS, Continued

Coaxial Connectors	Coaxial connectors are used for RF signals. Coaxial cables have an inner conductor, a dielectric layer surrounding the inner conductor, an outer conductor used as a shield, and an insulating outer jacket. Threaded couplings are used on most military coaxial connectors. Anything that alters the dimensions or concentricity of the dielectric or conductors can degrade the RF signal. Coaxial connectors are covered by MIL-C-39012.
Hermetic Connectors	Hermetically sealed connectors are for vacuum or high pressure conditions. Hermetic connectors usually have steel shells and steel contacts with a suitable finish. The inserts are usually formed from compression glass, which has excellent insulating properties, and can be molded to the connector body. The coefficient of thermal expansion of the shell, contacts, and insert must be compatible to maintain a proper seal. Contacts have eyelet or solder cup ends. Hermetic styles can be found conforming to MIL-C-5015, MIL-C-38999 and MIL-C-24308.
Integral EMI Filter Connector	These connectors usually contain one or two multilayer ceramic capacitors in the shape of the connector. The periphery of the capacitor is metallized and is soldered to the shell to make the ground connection. Metallized through-holes are fabricated in the body of the cap where the connector pins are inserted and soldered, each providing capacitive coupling to ground. The dielectric is typically based on barium titanate ceramic with palladium/silver electrodes. The capacitors are brittle and susceptible to cracking and chipping.

MATERIALS

Contacts	Contacts are made of a base metal protected by a relatively thin protective plating. Typical base materials are beryllium-copper, phosphor-bronze, spring brass, and low-leaded brass. Gold is commonly used as a protective plating material.
Insert	Common insert materials are diallyl phthalate, silicone rubber, and neoprene. Typical properties of connector insert materials are shown in Tables 4.1 and 4.2. The data in these tables was adapted from [4.3].

Table 4.1 Mechanical and Environmental Properties of Selected Connector Insert Materials.

Property	Units	Diallyl Phthalate	Silicone	Epoxy
Tensile Strength	psi	5000-10000	4000-5000	5000-7000
Compressive Strength	psi	20000-30000	10000-15000	18000-25000
Thermal Conductivity	10^4 W/cm-°C	29.3-41.8	31.4	29.3-75.3
Thermal Expansion	10^{-5} in/in per °C	2-3	0.8	2.5-5.0
Resistance to Heat	°F °C	350-500 177-260	600 316	300-500 149-260
Water Absorption	% in 24 hours	0.1-0.3	0.1-0.2	0.1

Continued on next page

MATERIALS, Continued

Table 4.2 Electrical Properties of Selected Connector Insert Materials.

Property	Units	Diallyl Phthalate	Silicone	Epoxy
Volume Resistivity	Ω - cm	10^{13} - 10^{16}	10^{10} - 10^{14}	10^{14}
Dielectric Strength	V/mil	395-450	200-400	300-400
Dielectric Constant	at 60 Hz	4.3	3.3-6.2	3.5-5.0
Dissipation Factor	at 60 Hz	0.01-0.05	0.004-0.03	0.01
Arc Resistance	seconds	125-180	150-250	150-190

MILITARY SPECIFICATIONS

Introduction Military connectors for electronic equipment are designed for a variety of applications. Some of the common applications are described briefly below. Table 4.3 lists the military specifications for many of the basic connector types. In addition, MS numbers (style numbers) exist to describe the variations on each basic type.

Military Specifications Table 4.3 lists military specifications covering all types of connectors. Series and class designations may be used for specific connectors configurations within a given specification. The order of the identification scheme is as follows:

MIL-C-38999	Basic Specification
Series	I, II, III, IV
Class	Special features

For example, MIL-C-38999, Series III, Class Y is a hermetically sealed cylindrical connector with a corrosion resistant steel shell.

Once the applicable standard has been identified, the part number marked on the connector shell can be used to identify the contact configuration, the shell material and coating, and other features.

Each specification generally includes material requirements, electrical test and performance requirements, part number variants, and mechanical data.

Continued on next page

MILITARY SPECIFICATIONS, Continued**Table 4.3** General Classification of Military Connectors.

MIL-C-5015	Circular Threaded
MIL-C-21097	General Purpose
MIL-C-22992	Waterproof, Quick Disconnect
MIL-C-24308	Miniature Rack & Panel
MIL-C-26482	Environment Resistant
MIL-C-26500	High Reliability
MIL-C-28731	Blade & Fork Type
MIL-C-28748	Rectangular Rack & Panel
MIL-C-28804	High Density, Jack Screw
MIL-C-28840	High Shock Shipboard
MIL-C-38999	High Density, Circular, Environment Resistant
MIL-C-39012	RF Coaxil
MIL-C-39029	Contact Pins
MIL-C-81511	Circular, Environment Resistant
MIL-C-81659	Rectangular, Environment Resistant
MIL-C-83513	Microminiature, Rack & Panel
MIL-C-83723	Circular, Environment Resistance
MIL-C-83733	Rectangular, Environment Resistant, 200°C
MIL-C-85049	Connector Accessories

SECTION B

FAILURE CHARACTERISTICS

OVERVIEW

Introduction Proper connector operation requires the correct operation of, and interaction between, the contacts, insulators and mechanical components. A failure of any one of these components may result in an identical failure characteristic affecting the entire connector assembly. For example, a single circuit connection may fail due to corrosion on the pins, failure of a retention device that holds a pin in the insert, or a broken connection to external wiring. In this section we will focus on the main characteristics and outline the individual conditions which can cause a failure.

Pre-Accident Data In most connectors, the insert and contact pins are sealed off from the outside environment. Metal shells provide protection from impact damage, fire, and fire-fighting liquids. Therefore, conditions which existed before the accident should remain reasonably well preserved.

Contents This section covers the following characteristics:

- High Contact Resistance
- High Leakage Current
- Corrosion
- Chemically Induced Ignition

HIGH CONTACT RESISTANCE

Basis	High contact resistance is usually detected by electrical resistance measurements. In this discussion, we consider the resistance measured between conductors on either side of the mating parts of the connector. This measurement includes the resistance of the wire connections to the contact pins. Sometimes, it is measured directly at the exposed end of the contact pins, the solder cup, or crimp band.
Condition	There are several possible causes for high contact resistance: <ul style="list-style-type: none"> • corrosion • poor mating of the contact pins • degraded crimped or soldered joints attaching the pins to the connecting wires
Mechanism	Corrosion is usually caused by improper sealing of the connector, and subsequent exposure to conductive contaminants. The specific mechanism of corrosion is discussed in a later subsection. <p>Crimp connections fail due to over- or under-crimping, if the wire is nicked or broken in the crimp sleeve, or if the wire is not properly strain-relieved. A satisfactory crimp should provide a gas-tight seal around the conductor.</p> <p>Poorly made solder joints can fail from exposure to vibration and thermal shock. The two main reasons for solder joint failure are improper soldering workmanship and contaminants in the solder or on solderable surfaces.</p>
Discussion	Most contacts in avionic systems are crimped. Crimp failures are usually associated with improper crimp tool use. Insufficient crimp force causes a loose wire-to-contact fit that can lead to wire pull-out or intermittent resistances. Over-crimping can crack the contact body or reduce the cross-section of the wire and cause wire breakage. In either case, intermittent contact or high contact resistance can result. <p>Contacts may also be soldered using a solder-cup terminal, which is an integral part of the connector. Solder joint failures can be caused by improper cleaning of the joints prior to soldering, incorrect temperature control during the soldering operation, or contamination by metals or organic compounds. Any of these can degrade the mechanical strength of the joint and lead to cracking, intermittent contact, or high contact resistance.</p>
Precautions	Due to the low melting point of solder, visual examination of solder joints may be useful only when little or no exposure to post-impact fire has occurred.

Continued on next page

HIGH CONTACT RESISTANCE, Continued

Analysis Radiography, electrical resistance measurements, and cross sectioning can be used to examine the contact connection to evaluate the workmanship.

SEM/EDS analysis can be used to identify contaminants in the solder.

Tensile pull testing is an effective way to verify the integrity of a connection between a wire and its associated terminal.

Data Eutectic solder is a 63 Sn/37 Pb alloy and has a melting point of 183°C (361°F).

Gold Stannate (AuSn_4) is a common intermetallic that forms at the gold/solder interface. It is a brittle material that degrades the solder joint. Microscopically it appears as large, white crystals intermixed with the solder [4.4].

Examples The contact pin cross section in Figure 4.2 shows the plating structure. The figure illustrates the advantage of the SEM backscatter emission (BSE) image in which elements of higher atomic number appear brighter. The contact pin has a thin gold layer over silver on the copper base metal. Mechanical defects, abrasion, and corrosion can generally be seen with this type of examination.

Microfocus x-ray analysis can be useful in identifying soldering problems. Figure 4.3 shows a connector where excess heat was applied after soldering during a heating cycle used to cure marking ink. This caused the solder to be wicked out of the cup and onto the wires, degrading the connection. [4.5]

Continued on next page

HIGH CONTACT RESISTANCE EXAMPLES

Figure 4.2 SEM backscatter image of the cross section of a contact pin showing plating thickness. Magnification: 1000X.

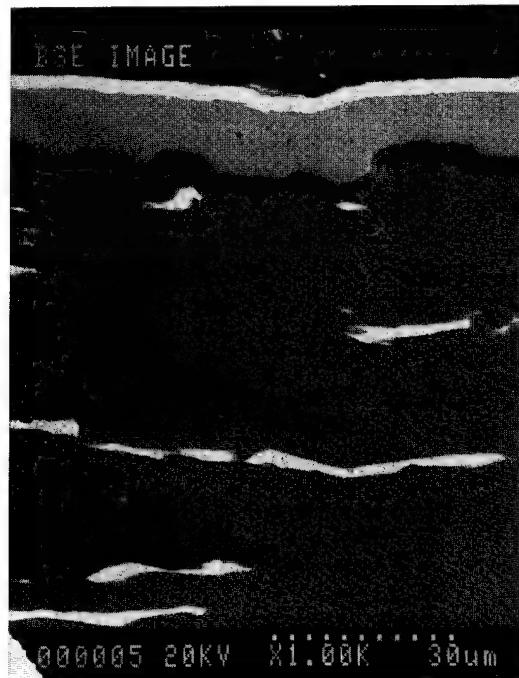


Figure 4.3 Microfocus x-ray radiograph of solder reflow anomaly on a connector. Note the missing solder in alternating contacts. Magnification: about 5X.



INSULATION RESISTANCE

Basis	When the resistance of the insulation material falls significantly below its normal value, undesirable leakage currents can flow between energized parts of the connector. Resistance measurements made between contact pins, or between the pins and the shell, usually indicate the condition of the insulation material. Abnormally low values may indicate a potential failure of the connector.
Condition	Decreased insulation resistance is usually caused by contamination. Other causes include failure of the insert material and broken or damaged contact pins.
Mechanism	When the resistance of the insert material falls significantly below its normal value undesirable leakage currents can flow between energized parts of the connector. The product of the voltage between the pins and the leakage current produces heat which can degrade the insert material, and thereby lower its resistance. As the insulation resistance decreases, more heat is generated. Eventually more contacts become involved, leading to severe arcing. The problem can be initiated by any one of several factors. Contaminants, moisture, ionizing radiation, and thermal aging all have a degrading effect on the mechanical and electrical properties of insulating materials [4.6]. Ionizing radiation can cause polymers to break down chemically, and cause cracking and decreased resistance.
Precautions	Contaminants combine with moisture to form a partially conductive layer on the surface of the insert. Usually the layer is composed of small deposits of conductive material separated by relatively clean areas of the insert. Small electrical discharges occur between the individual deposits, eventually causing the insulation to break down. Conducting tracks grow progressively across the surface, eventually bridging the contacts and causing complete electrical breakdown. Resistance measurements may not be able to identify incipient insulation contamination problems. This is especially true of measurements made in the field with low voltage multimeters. Most battery operated multimeters do not supply enough voltage to break down partially degraded insulation materials. Dielectric withstand voltage measurements may be needed to determine the extent of the insert materials degradation. See the discussion on the next page.

Continued on next page

INSULATION RESISTANCE, Continued

Discussion The military specifications call for two distinct measurements to test the integrity of the connector insulation system: insulation resistance and dielectric withstand voltage. Insulation resistance is measured at 500 Vdc. The resistance is then computed from the voltage and measured leakage current. Dielectric withstand measurements use high voltages, usually in excess of 1000 Vac, to confirm that the material will not break down when subjected to high voltage stresses.

Analysis Electrical measurements are the best method for detecting and identifying insulation resistance problems. Insulation resistance and dielectric withstand voltage tests may also be used. Comparisons between new and used, but functional, connectors may be helpful.

SEM/EDS may identify traces of metal or salts on the insulation.

More specific analyses may be made using Infrared Spectral Analysis.

Data The insulation resistance of a typical connector exceeds 1000 M Ω . Hermetically sealed connectors usually have slightly lower insulation resistance requirements on the order of 200 M Ω .

Dielectric withstand voltages are usually above 1000 Vac rms.

Examples Figure 4.4 shows a connector which failed from insulation breakdown. The insert material has cracked and decomposed near three adjacent pins on the left side.

Figure 4.5 shows the damage at the rear of the insert.

Continued on next page

INSULATION RESISTANCE EXAMPLES, Continued

Figure 4.4 Decomposition and cracking of a connector insert occurring as a result of wire insulation breakdown. Magnification: about 3X.

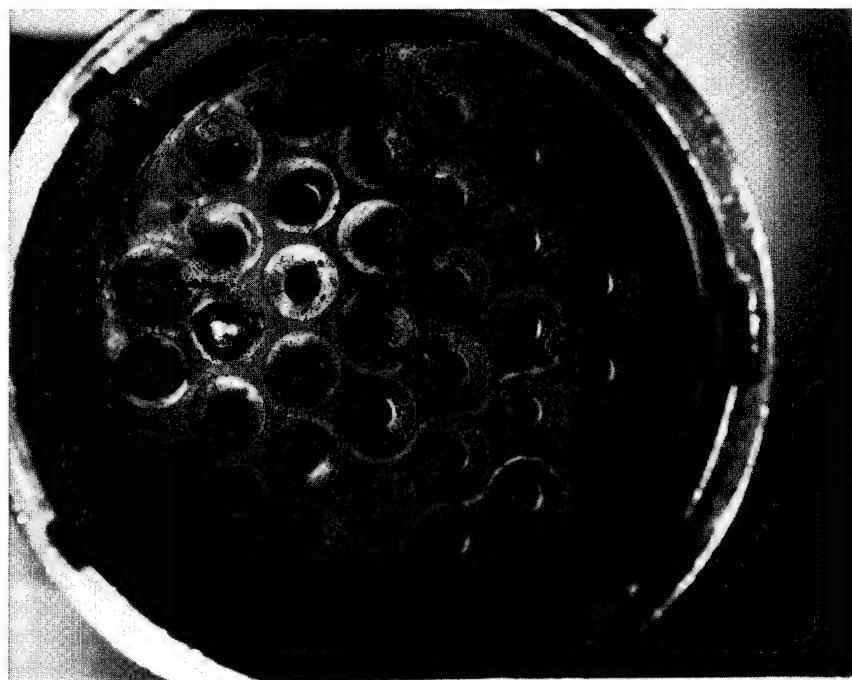
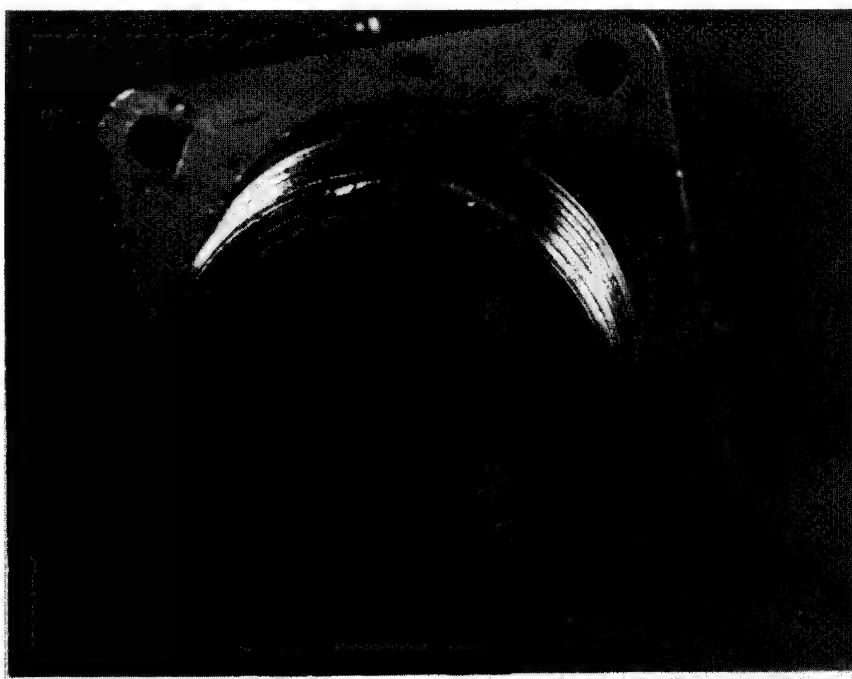


Figure 4.5 Damage to insert at the rear of the connector after wire insulation breakdown. Magnification: about 2X.



CORROSION

Basis One of the fundamental problems which affects connectors on all military aircraft is corrosion [4.7]. Moisture and bulk fluids which occasionally enter connectors can cause contact pin corrosion, compromise insulation resistance, and result in a variety of failure characteristics.

Condition The primary cause of corrosion is contamination, combined with moisture.

Mechanism Corrosion can cause deterioration of the mating surfaces of contacts, thereby increasing contact resistance. Corrosion on a connector can also reduce the insulation resistance between contact pins.

Three things must be present in order for corrosion to take place. These are a galvanic couple, a sufficiently conductive contaminant, and moisture. Many connector materials readily form galvanic couples which can foster corrosion. The reactivity of galvanic couples can be found in [4.8]. Contaminants are typically ionic, but covalent polar materials such as organic acids and salts may also initiate corrosion.

Gold plating normally found on military connectors is virtually immune to mild alkalais and salts. Access to the base metal or nickel underplate is sufficient for some contaminants to start the process. Silver and tin are also common platings which are more susceptible to corrosion than gold.

The corrosion process may be outlined as follows [4.9]:

1. Porosity occurs during the gold plating process.
2. Abrasive contaminants and handling exacerbate the plating damage.
3. Contaminants enter the connector and are deposited on the contacts.
4. Exposed base metal reacts with surface contaminants in the presence of moisture.
5. Corrosion processes degrade the electrical and structural integrity of the contacts.

Continued on next page

CORROSION, Continued

Discussion A literature search revealed a study [4.9] of the effects of corrosion on the following materials:

1. Gold plated onto copper base metal
2. Gold plated onto silver base metal
3. Gold plated onto copper with a silver barrier layer

A summary of the findings is presented below:

1. Gold-plated silver contacts showed signs of silver migration as revealed by EDS analysis.
2. In gold-plated copper contacts with silver underplating; migration of silver from the underplate to the surface, and its reaction with sulphur or chlorine from air pollutants, can be catastrophic.
3. Contamination begins to develop in the active contact areas, even though no pores in the plating can be observed.
4. Corrosion progresses faster in operating contacts, than in non-operating contacts due to the acceleration of ion migration by electric fields.

Data A few contaminants and their effects are listed below [4.8].

- Engine fuel (JP-4, JP-8): Corrosion and reduced insulation resistance from sulphur
- Hydraulic Fluid: degraded contact resistance
- Dielectric Coolants: degraded contact resistance and corrosion
- Anti-icing Fluids: Corrosion and reduced insulation resistance from ionic and organic salts
- Maintenance Fluids: corrosion and reduced insulation resistance from cleaners, detergents, and strippers
- Fire Suppression Fluids: corrosion and reduced insulation resistance
- Moisture and pollutants: Corrosion and reduced insulation resistance from sodium chloride, potassium chloride, sulfides and other types of ionic compounds

Precautions Visual inspection of mated connectors is not always a good indication of their condition because of possible internal damage that may be hidden from view.

Separation of the connector halves should be done in the laboratory, rather than in the field, to preserve the condition of internal components.

Analysis SEM, EDS and electron probe microanalysis (EPMA) can be used to study the onset of corrosion.

Auger electron spectroscopy and laser microprobe analysis are described in [4.10]. In that report, EDS X-ray maps showed chlorine and sodium present in the nickel underplate of gold plated contacts.

Continued on next page

CORROSION EXAMPLES

Examples Figure 4.6 shows the effects of corrosion on a gold plated connector pin which has been intentionally etched with HNO_3/HCl .

EDS maps of the same connector pin at higher magnifications were prepared. Figures 4.7 and 4.8 show the gold and copper maps which illustrate the effect of corrosive agents on contacts.

Figure 4.6 Effect of acid etch on gold plated contact pin. Magnification: 35X.



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CORROSION EXAMPLES, Continued

Figure 4.7 Gold EDS map of etched connector pin. Magnification: 70X.

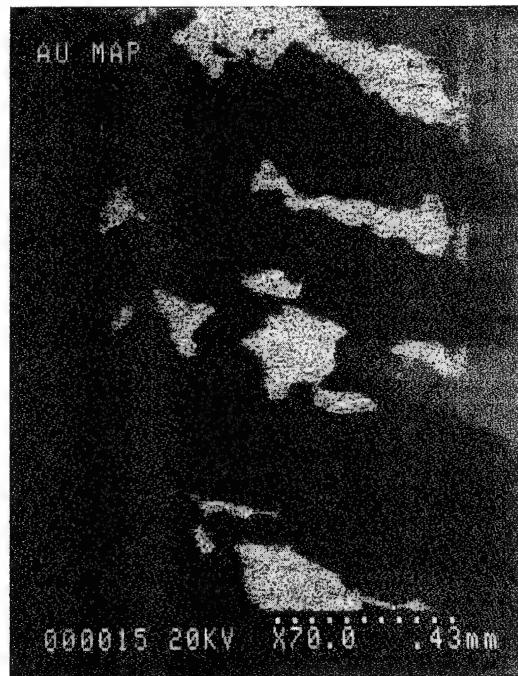
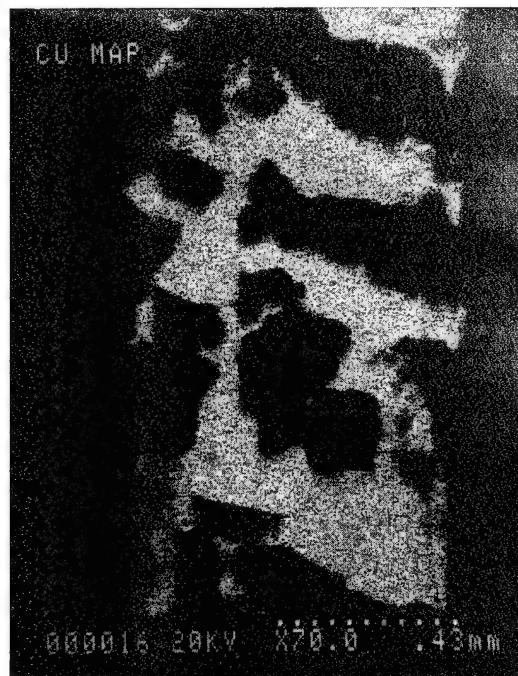


Figure 4.8 Copper EDS map of etched connector pin. Magnification: 70X.



CHEMICALLY INDUCED IGNITION

Basis	A hazardous condition results from the chemical reactivity of silver-plated copper wires in contact with Glycol/water solutions [4.11]. At one time, these solutions were in common use for cooling system applications and for deicing of aircraft.
Condition	A potential hazard exists when Glycol/water solutions come in contact with silver-covered conductors carrying direct current.
Mechanism	The Apollo environmental control system used a eutectic mixture consisting of 62% ethylene Glycol and 38% water. This mixture carried the trade name RS-89a. It also contained trace amounts of a pH buffering agent called TEAP and a copper chelating agent called NACAP. Ethylene Glycol evaporates very slowly because of its low vapor pressure in air. It leaves behind a residue which is both hygroscopic and conductive. The conductivity results from the sodium and phosphate ions contributed by the two additives.
	When subjected to dc current, the residue breaks down in a violent exothermic reaction. A detailed description of the chemical reactions involved can be found in [4.11].
Precaution	The specific solutions causing this hazard are no longer approved ; they may, however, be used accidentally.
Discussion	This hazard was initially discovered after the Apollo-Saturn 204 incident in January 1967. The investigations demonstrated that bare or defectively insulated silver-covered wires carrying a direct current potential produced ignition when contacted by Glycol/water fluids. A similar hazard does not exist with pure copper, nickel-covered copper, or tin-covered copper wires in electric circuits.
Data	The positive contact must contain silver.
	The mechanism does not occur with ac voltages.
Analysis	Analysis of the Glycol solution and the specific additives required to cause this hazard is best conducted by infrared spectral analysis.
Examples	Several examples are presented in [4.11].

SECTION C

FAILURE ANALYSIS PROCEDURES

OVERVIEW

Introduction This section outlines steps for field and laboratory examination of connectors and includes some specific analysis procedures.

Field Examination Guidelines and precautions for field examination and handling are provided. Obtaining accurate documentation while minimizing damage to the connector is an important factor. A suggested list of data to describe for each connector selected for laboratory analysis is included.

Laboratory Procedures An outline of the basic steps for laboratory examination is provided.

Analysis Procedures The following analysis procedures are covered at the end of this section:

- Contact Resistance
- Insulation Resistance
- Dielectric Withstand Voltage
- Corrosion
- Contact Sample Preparation

Procedures for standard electrical and chemical tests can be found in [4.12].

FIELD EXAMINATION

Introduction Field examination must be limited to what the investigator can see or measure with the limited tools that are available. Careful visual examination is essential. A multimeter is the most practical instrument for preliminary electrical measurements.

The purpose of the field examination is to identify any connectors that should be removed for laboratory analysis. Information concerning a connector may become vital during an investigation if it is suspected that:

- it was the ignition source for a fire
- it contributed to the failure of an on-board system

Connectors do not inherently provide information about the status of aircraft systems, but their relationship to other aircraft components and systems may be important.

What to look for

The following visual indications suggest that laboratory analysis be conducted:

- signs of corrosion or discoloration of the shell
- indication that fluids that may have dripped on the connector
- signs of discoloration in the attached wiring
- unexplained malfunctions in the attached equipment

Precautions

Generally it is a good idea to leave the connector undisturbed, with its halves mated. This will give the laboratory the best opportunity to identify problems that may have existed prior to the mishap.

Documentation Recording the type and location of the connector and its relationship to other aircraft components and systems may be important. Hand sketches and photographic records are recommended.

A list of suggested information to obtain for each connector is presented in Table 4.4. Be sure to record this information and tag the connector and mating cables with an ID number when the connector is removed.

Removal

In the case of small removable equipment such as a small LRU (Line Replaceable Unit), it's best to remove the connector intact, with all the mated connector parts mounted on the equipment.

If the connector is integral with a wire bundle, then segments of the bundle should be removed too. Cut the bundle, leaving at least one foot on each side of the connector. The bundle ends should be marked on both sides of the cut for later identification.

Continued on next page

FIELD EXAMINATION, Continued

Table 4.4 Sample Connector Identification Form

Aircraft	<i>F111</i>
Sample ID#	<i>Conn 101</i>
Date of Mishap	<i>04/03/90</i>
Date Removed from Site	<i>04/03/90</i>
Connector Type	<i>38999</i>
Style	<i>Series II</i>
Location Found At Site	<i>connected to TFR</i>
Bundle Label	<i>Conn 101-A (free end)</i>
Panel or Instrument Name	<i>TFR Unit</i>
Contact Pin Function	<i>J1 - Flight Control etc.</i>
Manufacturers Name	<i>ITT</i>
Manufacturers Part Number	<i>D38999-20-F-C-35-P-B</i>
MS Number	<i>MS27474</i>
Date Code	<i>7024</i>
Comments	<i>TFR not working? Hydraulic fluid spill near connector</i>
Contact Pin Functions	<i>J-1 - Flight Control (15 VAC) etc.</i>

LABORATORY EXAMINATION

Steps The following steps assume that the connector halves have not been separated, and are still in their post-accident state. In addition, access to wiring is needed to make resistance measurements.

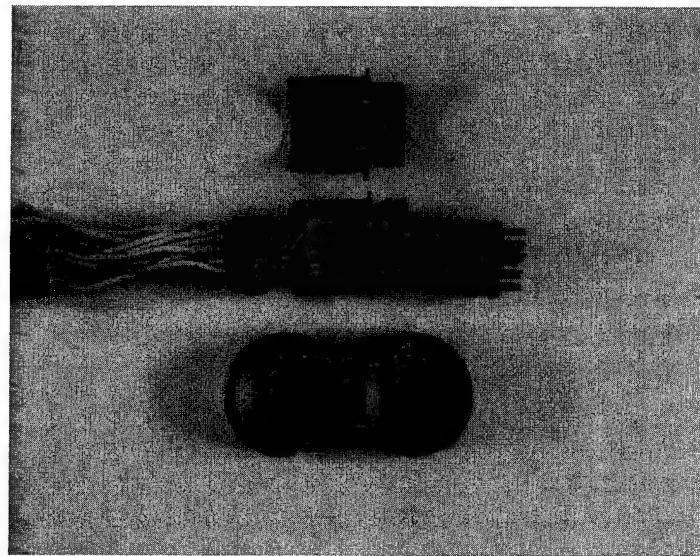
1. Visually examine the outside of the connector and wiring, noting any signs of corrosion, discoloration, melting or contaminants.
2. Visually examine solder joints or crimps.
3. Remove the connector from panels or mounting brackets, if applicable.
4. Prepare an x-ray radiograph to verify any gross internal damage.
5. Perform contact resistance measurements.
6. Conduct insulation resistance tests.
7. Conduct dielectric withstand voltage tests.
8. Separate connector and visually examine contact pins and insulator surface.
9. Perform SEM/EDS analysis of contacts and insulator if considerable contact abrasion or corrosion is suspected.
10. Conduct IR spectral analysis to identify specific contaminants.

Disassembly Impact damage may make it impossible to separate the connector halves without damaging the connector. In this case, it may be necessary to cut the connector shell to separate the mating halves. Small, hand-held metal saws can be used effectively. Panel-mounted connectors may need to be removed from panels to facilitate separation.

Continued on next page

LABORATORY EXAMINATION EXAMPLES

Figure 4.9 Parts of a connector shell cut open to facilitate disassembly. Magnification: about 0.5X.



CONTACT RESISTANCE

Measurement Preliminary contact resistance measurements can be made in the field or laboratory using a conventional multimeter.

Formal measurements should be made in accordance with MIL-STD-1344 for consistency. There are two procedures. Limits for the test values are found in the specification for each connector.

Low Level Signal Contact Resistance: A low dc test current is applied to several pairs of contacts in series. The source has a 1 mA short-circuit current and a 20 mV open-circuit voltage.

Contact Resistance: A test current is applied to a single set of mated contact pins. The current ranges from 1 to over 200 A, depending on the pin and wire sizes.

Typical Values For 12 gauge contacts meeting MIL-C-38999, the test current specified is 17 A. The maximum voltage drop is 85 mV when new, or 100 mV after environmental tests [5 $\text{m}\Omega$ - 6 $\text{m}\Omega$].

Precaution Contacts can develop thin oxide films which make them appear to have a high resistance at low voltages. The resistance decreases slowly as the voltage is increased, and then drops sharply when the voltage reaches a certain level. The voltage at the point when the resistance suddenly drops is called the *fritting voltage* [4.9].

It may be meaningful to make electrical resistance measurements on a connector to determine its pre-impact condition. For these measurements to be useful, the connector must be relatively undamaged by impact and post-impact handling. It is important that the connector halves remain mated after impact. The effect of contact wiping due to separation may render electrical measurements meaningless.

INSULATION RESISTANCE

Measurement The procedure from MIL-STD-1344 is to apply 500 Vdc between specified metal parts of the connector, and measure the resulting leakage current. The insulation resistance is computed from the measured leakage current and the applied voltage. The test is conducted twice: once between the most closely spaced contact pins, and a second time between the shell and the contact closest to the shell. Required test result values are found in the connector specifications.

Typical Values The minimum acceptable insulation resistance for connectors meeting MIL-C-38999 is 5000 M Ω . The minimum acceptable level after humidity tests is 100 M Ω .

Precautions Voltage application time and leakage current should be limited. The test may cause continued breakdown of the insulation material.

DIELECTRIC WITHSTAND VOLTAGE

Measurement The procedure is to apply a high voltage to the connector and verify that no damage results. The voltage is usually at 60 Hz ac, and the required voltage levels are given in the connector specifications.

Typical Values Connectors meeting MIL-C-38999 are tested between 1300-2300 Vac, depending on their service rating. The voltages is adjusted to account for altitude conditions. The stated numbers are at sea level.

Precaution These tests are generally destructive, and should only be conducted on non-critical connector samples.

CORROSION

Measurement Corrosion on connectors removed from a mishap can be examined with the unaided eye, by optical microscopy or by SEM.

Porosity The investigator may wish to verify the susceptibility of a particular connector to corrosion by testing samples from the manufacturer. Porosity of gold plating is likely to be of interest, for example.

The standard military test procedure is described in MIL-STD-1344, method 1017. It involves immersing the plated contact pins in a 70% nitric acid solution. Nitric acid does not attack gold, but does attack silver, copper, and other base metals. If the gold plating is porous, the acid attacks the materials beneath the gold, and causes corrosion on the surface of the contact pin. The results are viewed at 10X magnification, using collimated light.

Other procedures can be found in ASTM B583-80 [4.13]. There are two tests using either Nitric acid vapor or sulphur dioxide vapor at high humidity levels. A third test uses an electrographic technique, referred to as a type of "gel-bulk electrography". The tests are suitable for coatings containing 75% or more of gold on substrates of silver, copper, nickel, and their alloys. The tests are all destructive in nature, and can only give qualitative results.

Example Figure 4.10 shows a hermetically sealed connector removed from an aircraft involved in a mishap. Reddish brown rust stains were found on the outside surface of the shell, near the locking pins.

Continued on next page

CORROSION, Continued

Figure 4.10 Rust stains on outside of a connector removed from an aircraft involved in a mishap. Magnification: about 2X. The arrow points to a rust stain.



CONTACT SAMPLE PREPARATION

Introduction Sample preparation consists of four basic steps which are outlined below.

- sectioning
- mounting
- grinding
- polishing

The parameters and materials for automatic polishing equipment are provided below [4.14]. Most of this information pertains to manual preparation as well. The principles of metallography and sample preparation methods are covered in [4.15].

Sectioning Al_2O_3 Cutoff Wheel/Coolant.

Mounting Bakelite, Epoxide, or Castable Mounting Media.

Grinding Table 4.5

SiC Grit Size	Time (secs)	Wheel Speed (rpm)	Pressure (psi)
240	60	300	40
600	60	300	40

Polishing Table 4.6

SiC Grit Size	Time (secs)	Wheel Speed (rpm)	Pressure (psi)
1 micron diamond compound/red felt/oil	180	250	30
Ferric oxide slurry/Lecloth	60	150	20

Continued on next page

CONTACT SAMPLE PREPARATION, Continued

Remarks	The ferric Oxide final polish is recommended for microscopic examination of polished samples, although it leaves a passive film which is inert to etching. A few turns on an alumina polishing cloth will remove the passive layer for etching purposes. Gamma alumina (0.05μ) can be used as the final polishing medium. The addition of a few drops of an etchant solution composed of 50 ml NH_4OH and 5 ml H_2O_2 will facilitate polishing.
Etchants	<p>Immerse the sample in a solution of 50 ml ammonium hydroxide (NH_4OH), and 5 ml hydrogen peroxide (30%) H_2O_2. NOTE: If etchant is too fast, add 50 ml H_2O. The immersion time needed to produce the desired etch effect can only be determined by experimentation.</p> <p>To differentiate between cuprous oxide and copper sulfide inclusions, examine the sample in the as-polished condition under polarized light. Cuprous oxide will be red, copper sulfide will remain dark. Both are medium gray under brightfield illumination.</p> <hr/>

SECTION D

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CHAPTER 5

PRINTED WIRING BOARDS

OVERVIEW

Introduction Printed wiring board (PWB) fabrication is a complex process involving a variety of material processing steps. From a failure analysis standpoint PWBs are one of the most complex structures that the investigator may encounter. They involve composite substrate materials, plating and soldering processes, high density electrical interconnections and sophisticated microelectronic devices. In addition, PWBs have significant mechanical and environmental stress in operation. Because of this complexity the mishap investigator has a variety of areas to examine when analyzing a PWB failure.

In this chapter we will review some of the fundamental processes used in printed wiring board fabrication, the materials used in those processes, and outline procedures for examining PWBs during mishap investigation.

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SECTION A

BACKGROUND

OVERVIEW

Introduction Printed wiring board (PWB) fabrication is a complex process involving a variety of material processing steps. One of the processes uses copper-clad laminates which are etched to produce circuit traces. The boards are drilled with automatic machinery, loaded with components and automatically soldered to complete the process. Although there have been a variety of new chemical processes in board structures that have evolved and pervaded military equipment in recent years, the final result of these new processes is a product similar to the one just described.

Additional material can be found in [5.1], [5.2] and [5.3].

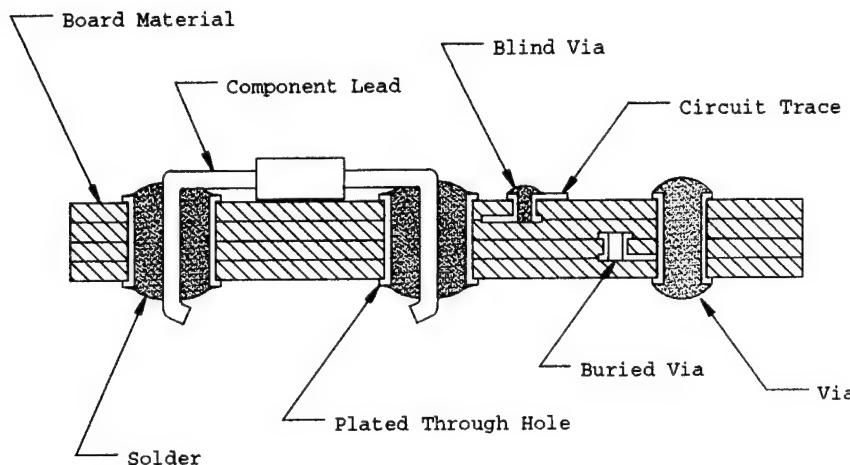
Contents This section is divided into six articles:

- Construction
- Fabrication Process
- Types of Printed Wiring Boards
- Solder
- Copper-Clad Board Material
- Standards

CONSTRUCTION

Overview A variety of PWB construction methods are used in military aircraft. There are three basic types which uses traditional construction methods. In order of increasing complexity these are: single-sided, double-sided and multi-layer boards. A simplified diagram of a multi-layer board is discussed below and illustrates features common to all three types.

Figure 5.1 Simplified diagram of a multi-layer printed wiring board.



Board Material The board material is an insulating substrate that provides mechanical support for components and electrical insulation between the circuit traces. A glass-fiber and epoxy resin composite (glass-epoxy) is the most common material.

Circuit Traces Circuit traces are copper patterns used to connect electronic components on the board. The connections are usually made by traces that interconnect component mounting pads or plated-through-holes.

Plated - Through-Holes Plated-through-holes perform two major functions. First, the holes provide a receptacle for component leads during the assembly process before soldering. Second, they provide a means for interconnecting traces on different layers.

Continued on next page

CONSTRUCTION, Continued

Vias

Vias are plated-through-holes on two-sided and multi-layer boards which are used to interconnect layers or traces, but are not used for component mounting. Vias are usually smaller in diameter than component holes. There are two special types of vias:

blind via: A blind via is visible from one exterior layer of the board. The other side of the via terminates on an interior layer.

buried via: A buried via is not visible from an exterior layer of the board.

Solder

Electrical solder is a eutectic tin-lead alloy used to attach components and improve the electrical and environmental properties of the circuit traces.

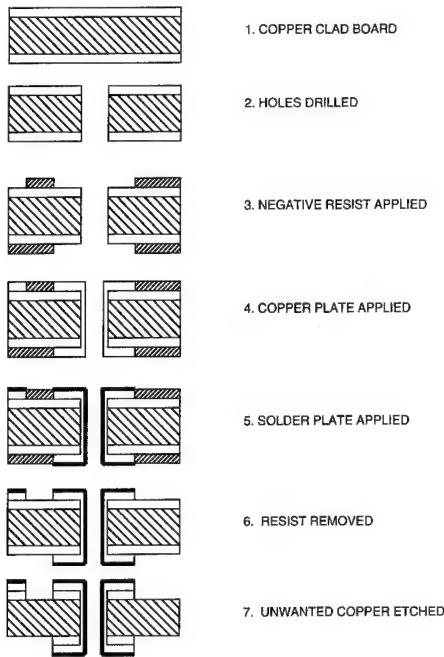
Solder can be applied manually or by automatic machinery.

When plated-through-holes are soldered, capillary action causes the solder to wet both sides of the board. This improves the mechanical strength of the hole and the component attachment, and also improves the reliability of the electrical connections.

FABRICATION PROCESS

Overview There are several PWB fabrication processes used for military products. One process is illustrated in Figure 5.2.

Figure 5.2 Steps in process for PWB fabrication.



Copper-Clad Board Material The process begins with a copper-clad substrate. Glass fiber with epoxy resin (glass-epoxy) or polyimide resin are common materials.

Drilling The PWB design is used to generate a drilling pattern for vias and through holes. Numerically Controlled (NC) machines drill the board in the appropriate sizes for the different hole types.

Resist Application The drilled board is coated with a pattern which resists copper plating in subsequent steps. In one process the copper-clad board is coated with a photosensitive emulsion. The emulsion is selectively polymerized by exposing the board to ultraviolet light using a photographic image of the circuit pattern as a mask. After the board is rinsed in a solvent the resist pattern leaves the board exposed where copper traces are to be plated. The resist pattern is a photographic negative of the circuit traces.

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FABRICATION PROCESS, Continued

Copper Plating	The board is immersed in a chemical solution which coats the bare surfaces of the drilled holes with copper. This is called electroless copper because electric power is not used for the plating.
	Additional copper is plated onto the board by electroplating. This increases the thickness of the plating on traces and in through-hole areas. In the plating process copper surfaces of the boards are connected to the cathode (negative potential) of the electroplating power source.
Solder Plating	Solder is electroplated onto copper as 60 percent tin - 40 percent lead. MIL-STD-275 requires that electroplated solder be at least 300 microinches thick.
Resist Removal	The resist is removed using solvents. This exposes the original copper clad on the board in areas where solder plate has not been applied.
Copper Etching	Acid etching removes the unwanted copper from the board, leaving behind circuit traces and plated through holes. Solder plate resists the etching process so that only the unwanted copper is attacked by the etchant.

TYPES OF PRINTED WIRING BOARDS

Overview Many types of PWB construction can be found in military applications. Most of the common types fall into one of the categories described in the following discussions.

Through-Hole Traditional PWB construction uses copper-clad board materials to construct single-sided, double-sided, or multi-layer boards with copper circuit traces. Components are mounted with their leads passing through holes in the board.

single-sided boards have traces on one side only. The board material is one piece with holes for component leads. Inside surfaces of holes are not plated.

double-sided boards have traces on both sides. The board material is one piece with holes for component leads and vias which interconnect traces between the two sides. Inside surfaces of holes are usually plated. This is called plated-through-hole or PTH construction.

multi-layer boards have traces on both sides and interior surfaces. The multi-layer board or MLB can be visualized as several double-sided boards laminated together with intervening layers of unclad board material. Inside surfaces of component mounting holes and vias are plated.

Surface Mount Surface mount components have leads or may be leadless and are soldered onto pads on exterior surfaces of the board without using holes. PWBs using surface mount technology (SMT) are almost always multi-layer. Surface mount and through-hole mounting are sometimes mixed on the same board.

Flexible Circuit Flexible printed circuit boards or *flex circuits* are used for flexible circuit connections and for construction of PWBs with unusual shapes. Polyimide film is used almost exclusively as the substrate for flex circuits. In most cases copper circuit traces are laminated between two sheets of the film. Flex circuit construction can accommodate the mounting of both through-hole and surface mount components. The adhesive between the layers is typically a polyester material.

SOLDER

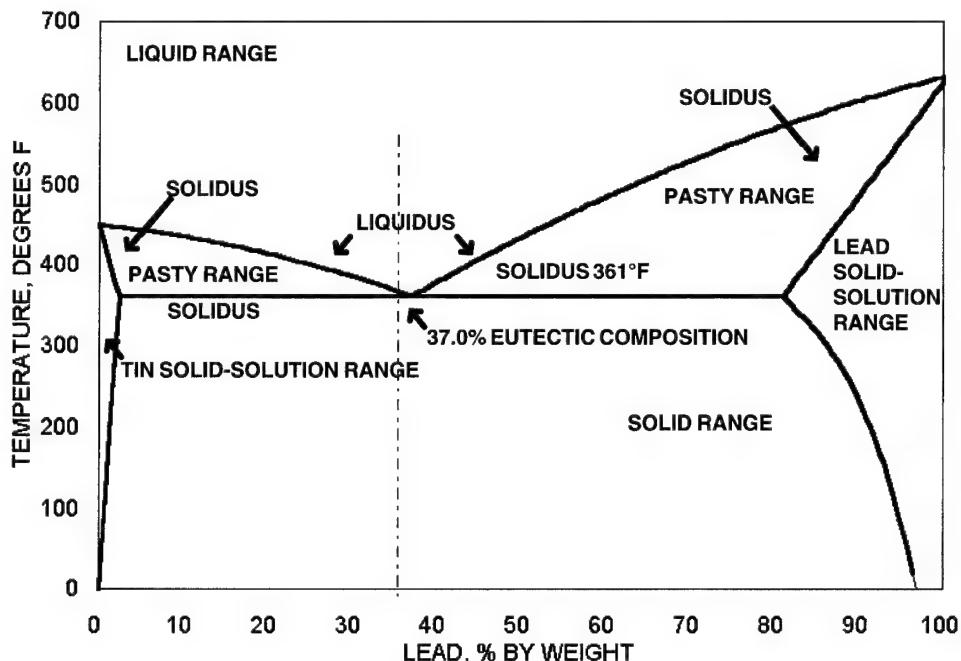
Overview Electronic solder is a eutectic alloy composed of tin and lead. A primary characteristic of a eutectic alloy is that it has a lower melting point than either of the two constituents.

Tin-Lead Alloy Eutectic solder is 63% tin, 37% lead by weight and has a melting point of 182 °C (361 °F). All other alloys, including pure tin or pure lead, have higher melting points.

Electronic solders are usually composed of tin and lead in ratios close to the eutectic point. When non-eutectic mixtures cool, the excess base metal solidifies first, leaving a eutectic alloy to cool at the reduced temperature. This usually results in internal stress and cold solder joints.

The phase diagram is shown in Figure 5.3 [5.1].

Figure 5.3 Phase diagram of tin-lead alloy used for electronic solder.



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SOLDER, Continued

Contaminants Metallic and nonmetallic contaminants are of concern in solder alloys. Contamination occurs during the solder process while the solder is in a molten state. Under normal conditions solder joints do not become contaminated after they are formed. But the effect of initial contamination can significantly reduce solder joint life.

Nonmetallic contaminants such as sulfides and oxides are formed by the reaction of the solder with sulfur and oxygen. These contaminants affect the flow characteristics of the solder and metallurgical characteristics of the joint.

The properties of solder are affected by small amounts of certain metallic contaminants. Some of these are discussed below [5.1]:

Copper: Copper forms two intermetallic compounds with tin: Cu_3Sn and Cu_6Sn_5 . The compounds weaken the solder joint and cause the solder to become sluggish and gritty.

Iron: Iron forms two intermetallic compounds with tin: $FeSn$ and $FeSn_2$.

Gold: Gold is readily soluble in molten solder and small percentages can cause brittle, dull solder joints. Percentages of copper and gold combined of more than 0.3% will degrade solder joints.

Zinc: One of the most detrimental of solder contaminants. As little as 0.005% zinc will cause grittiness, lack of adhesion and eventual failure of the joint.

Small amounts of nickel and aluminum can also degrade solder joints.

Standard Compositions Military standards require the use of certain standard solder compositions which are defined in the Federal Standard QQ-S-571.

COPPER-CLAD BOARD MATERIAL

Overview	Copper clad board material is the raw material from which almost all PWBs are made. The most common board material is a glass-epoxy composite.
Prepreg	The manufacture of glass-epoxy composite boards starts out with the glass fiber fabric. The fabric is impregnated or coated with resin, which is then polymerized to a point suitable for storage. The partially cured material is called "prepreg".
Foil	Copper foil is made by an electrodeposition process and supplied in rolls for lamination onto the prepreg. The foil and prepreg are pressed together in large heated presses at pressures exceeding 1000 psi to produce copper-clad board stock.
Cladding Thickness	The thickness of copper cladding is specified in ounces per square foot. MIL-STD-275 [5.4] requires that the board stock have a cladding thickness of 0.5 ounce copper. When the fabrication process is complete circuit traces must have a minimum of 1 ounce copper which is equivalent to a thickness of 0.0014 inches.

STANDARDS

Overview	The primary PWB standards are listed below.	
Military	Military standards and specifications cover materials, test methods, and standard board layout procedures.	
	MIL-STD-275	Printed Wiring for Electronic Equipment.
	MIL-P-55110	Military Specification for Printed Wiring Boards.
	MIL-STD-202	Military Standard Test Methods for Electronic and Electrical Component Parts.
	MIL-P-13949	General Specification for Plastic Sheet, Laminated, Metal Clad (For Printed Wiring Boards)
Federal	The composition of solder alloys is specified in this standard.	
	QQ-S-571	Solder, Tin alloy, Tin-Lead alloy, and Lead alloy.
ASTM	The American Society for Testing and Materials (ASTM) publishes test procedures for materials used in PWBs.	
	ASTM-E-53	Standard Method for Chemical Analysis of Copper (Electrolytic Determination of Copper).
	ASTM-B-487	Measuring Metal and Oxide Coating Thickness by Microscopic Examination of a Cross-Section.

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STANDARDS, Continued

IPC

The Institute for Interconnecting and Packaging Electronic Circuits (IPC) publishes many standards covering PWBs which are referenced in Military specifications. The primary IPC standards are listed here.

IPC-A-28/29	Single Sided Test Specimen.
IPC-A-28	Double Sided Test Specimen.
IPC-A-29	Multilayer Test Specimen.
IPC-A-600	Guidelines for Acceptability of Printed Boards.
IPC-A-804	Solderability Test Methods for Printed Wiring Boards.
IPC-CF-150	Copper Foil for Printed Wiring Applications.
IPC-S-815	General Requirements for Soldering Electronic Interconnections.
IPC-SM-840	Qualification and Performance of Permanent Polymer Coating (Solder Mask) for Printed Boards.
IPC-TM-650	Test Methods Manual.

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SECTION B

FAILURE CHARACTERISTICS

OVERVIEW

Introduction This section covers the physical features that can be observed when examining printed wiring boards during a mishap investigation.

Contents The section includes the following articles:

- Impact Damage
- Thermal Damage
- Contamination
- Thermal Expansion Mismatch
- Interconnection Failures

IMPACT DAMAGE

Observation Severe mechanical damage to PWBs can be caused by aircraft breakup and ground impact. Damage to electronic component packages and the PWB substrate are visible when examining the PWB.

Cause During aircraft breakup or ground impact severe mechanical loads are applied to electronic equipment. These loads are transmitted from the electronic equipment enclosure to the PWB and its components.

Mechanism Component damage occurs when the PWB is subjected to bending, twisting or shock loads. Shock loads on SMT boards can cause components to shear off the substrate at the solder joint. Component packages will usually crack on through-hole boards while the leads of the components may remain attached.

PWB damage can be observed in several fundamental forms:

- damage to component packages
- shearing or tearing of components
- cracking of the PWB substrate

Precautions None.

Discussion Impact damage will generally be so severe that no direct testing of the PWB or its components will be useful. The purpose of this material is to familiarize the investigator with the type of damage that can occur during impact.

Data None.

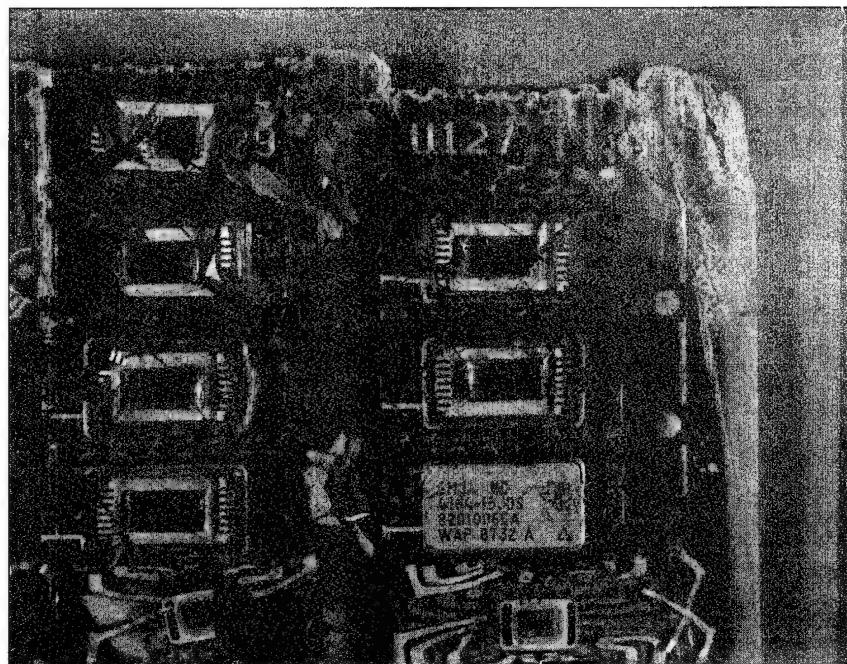
Analysis Examination can usually be conducted visually (with the unaided eye), or with a low power optical microscope.

Examples Figure 5.4 shows a multi-layer PWB that was subjected to tearing and cracking. It is a through-hole PWB and shows cracking of integrated circuit packages. This is a typical form of damage from bending the substrate.

Continued on next page

IMPACT DAMAGE EXAMPLES

Figure 5.4 Segment of a multi-layer PWB showing severe impact damage. Magnification: about 2X.



THERMAL DAMAGE

Observation Thermal damage to PWBs is caused by post-impact fire and other external heat sources or it can be caused by electrical failures on the PWB. The type and extent of damage can provide information about the heat source and its role in the mishap.

Cause Thermal damage to PWBs and their components can occur in several ways:

- external heat source outside an electronic enclosure
- direct exposure to PWB when boards are not enclosed
- electrical failure on PWB causing thermal damage

Mechanism Epoxy is a thermosetting material and thermal exposure above the temperature rating will cause chemical breakdown of the substrate material and eventual carbonization. Chemical breakdown is a time-temperature process and the rate of breakdown increases with temperature.

Most substrate materials can tolerate high temperatures for up to several seconds without noticeable damage. This is because it takes some time before the breakdown process can begin and because the thermal mass of the substrate and copper cladding will absorb some heat initially. Once thermally degraded the epoxy will behave more as a conductor, due to local carbonization.

Thermal damage to PWBs proceeds in several stages as the exposure becomes more severe. The process usually occurs in the following steps:

- discoloration
- solder melts
- cracking and charring of plastic component packages
- separation of circuit traces on exterior layers
- decomposition of the substrate
- separation of laminated layers on PWBs
- blackening and decomposition of the substrate material

Precautions Since chemical breakdown of the glass-epoxy substrate or other materials depends on time and temperature it is not possible to judge temperature accurately from the appearance of the PWB.

Even when PWBs are made from the same materials they vary greatly in thermal characteristics because of their size, shape and number of circuit layers. As a consequence any conclusion about thermal exposure should be verified by comparative tests on sample PWBs with the same configuration.

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THERMAL DAMAGE, Continued

Discussion	Thermal damage from electrical component failures on the PWB will be localized to the component and the circuit traces associated with it. This type of localized damage can usually be distinguished from the more uniform damage caused by post-impact fire.
Data	In glass-epoxy boards the epoxy resin will begin to break down thermally above approximately 250°C (482°F).
Analysis	Visual examination is usually sufficient. Low power optical microscopy may be useful in some cases.
Examples	Figure 5.5 shows a multi-layer PWB in which the substrate resin is completely decomposed. The individual layers separated during the decomposition process. Figure 5.6 PWB showing melted solder. This indicates board was heated prior to impact.

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THERMAL DAMAGE EXAMPLES

Figure 5.5 Multi-layer board in which the epoxy decomposed and layers separated. Magnification: about 1X.

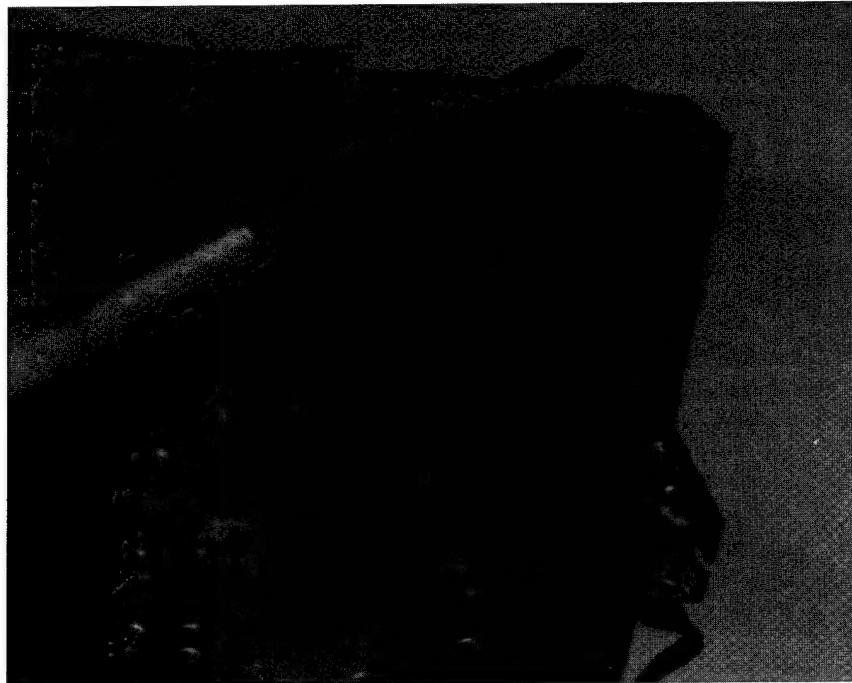


Figure 5.6 Melted solder displaced on PWB during impact. Magnification: about 2X.



CONTAMINATION

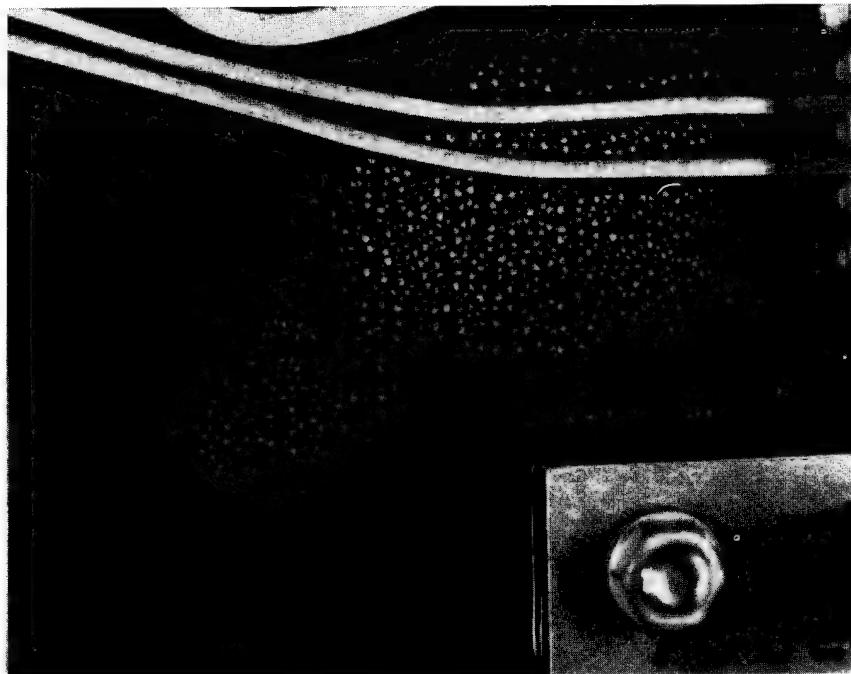
Observation	Contamination of PWBs can cause insulation degradation, corrosion and component failures. Frequently the symptoms and underlying source of contamination can be observed on the PWB [5.5]. Corrosion in the form of various oxides can be noted on severely contaminated PWBs, which are usually coated for environmental protection.
Cause	Contamination can be caused by problems in the manufacturing process or by unexpected environmental exposure in operation.
Mechanism	Contamination during the fabrication process can degrade the mechanical and electrical properties of the PWB and ultimately lead to failure. Contaminants come from several sources: <ul style="list-style-type: none"> • fingerprints, dirt, cleaning fluids from processing • metal slivers or solder bridges from assembly • moisture and salts from the environment Ionic contaminants become active in the presence of moisture or other fluids and may lead to conduction at higher humidity levels. Leakage current on PWBs can occur on the surface or in the bulk material of the laminate.
	Environmental contamination can lead to corrosion of copper circuit traces, damage to components and a rapid loss of the substrate electrical insulating properties.
Precautions	If contamination is suspected the PWB should only be handled with gloves and should be stored in an electronic-grade container.
Discussion	Over long periods contamination can lead to an effect called metal migration. There are two basic forms: <ol style="list-style-type: none"> 1. <i>Whisker growth</i> is a single crystal growth a few microns in diameter. 2. <i>Dendritic growth</i> occurs when a dc potential electrolytically transfers metallic ions between conductors. A metal dendrite forms on the cathode when the ions are reduced.
Data	None.
Analysis	Optical microscopy and SEM are the most common tools. In some cases electrical leakage measurements are used to detect electrical leakage as a symptom. Contaminants can usually be identified with SEM/EDS.

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CONTAMINATION EXAMPLES, Continued

Examples Figure 5.7 shows a fingerprint left on a PWB during processing. This is evidence of improper handling and cleaning prior to the conformal coating process.

Figure 5.7 Fingerprint left on PWB from incomplete cleaning during fabrication. Magnification: about 3X.



THERMAL EXPANSION MISMATCH

Observation Coefficient of thermal expansion (CTE) mismatch causes mechanical stress on electronic components, circuit traces and the PWB substrate. Stresses can lead to fractures in solder joints, plated-through-holes, internal traces and component leads.

Cause Mechanical failure of electronic components can be caused by exposure to extreme temperature variations. This can be caused by post-impact fire or repeated exposure to temperature variations not anticipated in the design of the PWB.

Mechanism All materials expand and contract with temperature changes. The rate or sensitivity to temperature is called the coefficient of thermal expansion or CTE. The CTE is usually expressed in % or ppm (part per million) per degree C of temperature change.

When materials with different CTE values are joined, mechanical stresses can arise from the dimensional change that occurs with temperature. Unless the joint fails the materials will be elongated or compressed to absorb the stress. The forces increase with several factors:

- the size of the assembly
- the difference between the CTE values
- the temperature variation

Precautions The CTE of organic materials can significantly change over the temperature range of -55°C to -200°C. This includes temperatures encountered in manufacturing as well as in the operational environment. It should be noted that the CTE of most metals does not significantly change over this temperature range.

Discussion CTE mismatch problems can be a life-limiting factor in some types of leadless surface-mount devices. In PTH technology component leads can flex and transfer stress away from the solder joint.

A method by which the fatigue life of solder joints can be predicted is covered in [5.2].

Component and PWB cracking are symptoms that appear occasionally in failures where extreme temperature variations have occurred. It is useful for the investigator to be aware of the basic mechanism involved so that it can be evaluated as a possible failure mode. Solder joint fatigue from CTE mismatch is one area of concern in industry.

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THERMAL EXPANSION MISMATCH, Continued

Data Table 5.1 below, lists the coefficients of thermal expansion for materials found on printed wiring boards.

MATERIAL	CTE (ppm/ $^{\circ}$ C)
Alumina	5-7
Epoxy-glass	12-16
Polyimide-glass	11-14
Copper-Invar-Copper	5-6
Copper-clad Molybdenum	5-6
Epoxy-Kevlar	6-7
Polyimide-Kevlar	5-7
Ceramic	5-7
Aluminum	22.9
Copper	16.5
Epoxy	45-65
Steel	10-13
Gold	14.2
Silver	19.6
Iron	12.2
Kovar	5.86
Solder 50-50	13.1

Analysis Cracking due to CTE mismatch may be visible with low power optical microscopy or SEM.

Examples None.

INTERCONNECTION FAILURES

Observation	Interconnection failures occur at solder joints, at the interface between layers on multi-layer boards and at the joints between traces and component mounting pads. These failures can appear as cracks in solder joints, as voids between layers and plated-through-holes, and as cracks on circuit traces.
Cause	Contaminants in solder, thermal stress, mechanical stress and process problems can cause interconnection failures.
Mechanism	<p>There are several basic mechanisms.</p> <ol style="list-style-type: none">1. Contamination in solder can result in mechanically weak solder joints. This can cause cracking or stress-related failures at stress levels below normal operating limits.2. Thermal excursions beyond the design limits of a joint can cause unanticipated mechanical stress due to thermal expansion mismatch.3. Mechanical stress can cause cracking in component leads, solder joints and copper circuit traces.4. Processing problems can lead to improperly filled solder joints in vias and plated-through-holes. This can lead to mechanical failure of the interconnection.
Precautions	None.
Discussion	The highest thermal stress seen by a PWB occurs in the production soldering process. The high thermal stress can crack PWB barrels or cause separation of the laminate.
Data	None.
Analysis	<p>Optical microscopy and SEM are useful for problems on external surfaces and solder joints.</p> <p>Real-time microfocus x-ray is a useful tool for general examination of the PWB, especially for problems within internal layers.</p> <p>Metallurgical sectioning and optical microscopy are usually used to examine layer registration and through-hole problems.</p>

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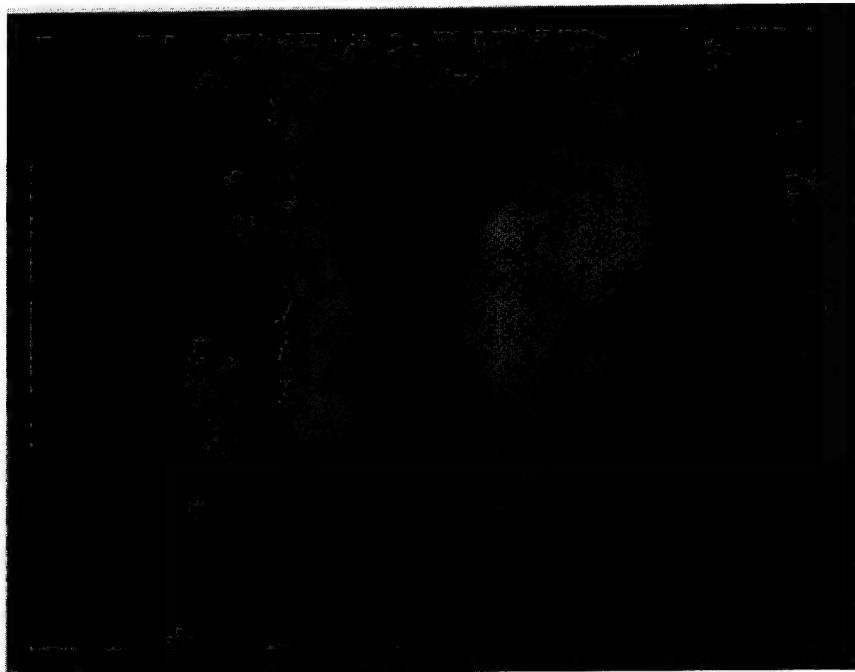
INTERCONNECTION FAILURES EXAMPLES

Examples A plated-through-hole incompletely filled with solder is shown in the microfocus x-ray radiograph of Figure 5.8. This is usually an indication of a wetting problem with the solder process and can cause the joint to be mechanically weak [5.6].

Figure 5.9 shows incomplete attachment of the hole wall to the inner layers on a plated-through-hole. This results in poor or missing connections to the layer and can cause intermittent failure of the electrical connection.

Figure 5.10 shows a cracked solder joint where the component lead enters the solder fillet. This results in intermittent electrical connection and circuit malfunction.

Figure 5.8 Microfocus x-ray radiograph showing incomplete solder filling in a plated-through-hole. Magnification: about 100X.



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INTERCONNECTION FAILURES EXAMPLES

Figure 5.9 Microphotograph of plated-through-hole showing incomplete attachment to internal layer of multi-layer board as shown by the arrow. Magnification: about 750X.



Figure 5.10 Optical microscope photograph of cracked solder joints on PWB. The box identifies one of the cracks. Magnification: about 10X.



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SECTION C

FAILURE ANALYSIS PROCEDURES

OVERVIEW

Introduction	This section outlines procedures for field and laboratory examination of PWBs and includes procedures for some of the specific analysis techniques.
Field Examination	Guidelines and precautions for field examination and handling are provided. Accurate documentation and minimum damage to the PWB are of primary importance. Special handling should be observed when the PWB includes non-volatile memory circuits. A list of data to collect for PWBs is included with the discussion on field examination.
Laboratory Examination	An outline of the basic steps for laboratory examination is provided. Detailed procedures for analysis techniques specific to PWBs is included.
Contents	<p>Field Examination Laboratory Examination Analysis Procedures</p> <ul style="list-style-type: none">• Conformal Coating Removal• Solder Joint Examination• Insulation Resistance Test• Metallurgical Sample Preparation

FIELD EXAMINATION

Introduction Field examination of PWBs is extremely limited because of their complex structure and the density of electronic components. For that reason laboratory examination should generally be conducted whenever the PWB may provide clues useful to the overall investigation.

Documentation Recording any identifying numbers on a PWB and the associated electronic chassis are essential steps in the documentation process. PWBs will generally be marked with an Assembly Number and a Serial Number which are both critical to record if the PWB is separated from the equipment.

Removal PWBs should not be separated from electronic equipment unless absolutely necessary. The separation can cause damage to electronic components on the PWB and obscure the condition of the circuits. If separation is necessary, tag the PWB and associated electronic chassis for identification.

PWBs should be wrapped in antistatic plastic bags before packaging for shipment to the laboratory. Under no circumstances should a PWB be wrapped in a non-conductive material.

Precautions The following general precautions should be followed for any type of PWB and may be especially important in preserving data on PWBs which contain non-volatile memory devices:

- enclose PWB in anti-static bag prior to handling/shipment
- do not remove or disconnect on-board batteries
- do not expose to x-rays or intense UV radiation
- do not short or connect to card-edge connectors

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FIELD EXAMINATION, Continued

Table 5.2 Printed Wiring Board Identification Sample Form.

Aircraft	<i>F-15</i>
Sample ID#	<i>PWB 101</i>
Date of Mishap	<i>04/30/90</i>
Date Removed from Site	<i>04/30/90</i>
Location at Site	<i>Adjacent to Right Side Engine</i>
Assy#	<i>09344 Assy-39765-39A</i>
Serial #	<i>313</i>
LRU or Chassis Function	<i>Engine Control</i>
Type of PWB	<i>Multilayer with int ground plane</i>
Overall Size	<i>5" x 11"</i>
Comments	<i>Burned circuit traces to Power Transistors</i>

REMINDERS FOR FIELD HANDLING

- **enclose PWB in anti-static bag prior to handling/shipment**
- **do not remove or disconnect on-board batteries**
- **do not expose to x-rays or intense UV radiation**
- **do not short or connect to card-edge connectors**

LABORATORY EXAMINATION

Introduction The general steps for laboratory examination of PWBs are outlined below. Usually the examination will take place after some type of electrical failure has been identified. Many of the test are destructive and should be conducted on samples of the same type of PWB from other aircraft first. Complete photographic documentation is very important at this time.

Visual Examination Perform a careful visual examination of the PWB. Some features to look for are:

- cracking of the substrate. This indicates mechanical flexure and stress.
- overheated or discolored circuit traces. Usually an indicator of overcurrent.
- cracked solder joints. Suggests solderability or solder contamination problems.
- solder joints which are dull, have too much or too little solder. Usually an indicator of poor soldering technique, contamination or overheating.
- discolored components or substrate. May indicate overheating.

Microfocus X-ray Examination Once a specific area of the PWB has been isolated x-ray examination may be used to identify internal problems which may not be visible otherwise. Magnifications up to 200x can be obtained. Real time microfocus x-ray allows the board to be rotated to improve the viewing angle while the examination is being conducted. Some features to look for are:

- discontinuity or damage to traces
- incompletely filled vias or through-holes
- misregistered traces or component pads

Optical Microscopy Optical microscopy can help identify external defects or problems. Dendritic growth and metal migration can be examined on single and double-sided PWBs by transmitting light through the substrate to perform the examination.

Electrical Measurements Electrical measurements can be used to identify open traces, and fractured solder joints. Caution should be used to keep voltage and current to a minimum to avoid damage to the component being measured. Excessive leakage current due to contamination can also be measured and is covered in the article on insulation resistance.

Metallurgical Examination Problems with solder joints and internal defects on multilayer boards can be examined by sectioning and preparing metallurgical samples. The mounting and polishing procedures are covered later in this section. Solder failures, voids, cracks and internal trace connections are best examined after their presence has been identified by other means.

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LABORATORY EXAMINATION, Continued

SEM/EDS In some cases contamination on the surface of the substrate can be identified with SEM/EDS. The contamination can occur on the surface of the board or below the conformal coating. In the latter case the coating must be removed first and the EDS analysis done on a section of the board where the surface is exposed. Chlorine, sulfur, sodium and bromine are elements of interest which can usually be detected with the SEM. Bromine is used as a flame retardant in some materials.

Solder joints can also be examined for contamination using EDS. Sulfur, oxygen, copper, gold, aluminum and zinc are contaminants that can cause problems in solder joints.

The location of contaminants in the solder joint is critical. Solder joint fractures caused by contamination frequently occur in the intermetallic phase at the component lead and solder interface.

CONFORMAL COATING REMOVAL

Introduction The removal of conformal coatings may be a significant problem in mishap investigation. There are four methods for removing conformal coatings.

- Solvents
- Thermal Parting
- Abrasion
- Plasma Etching

Solvents Solvents such as xylene, trichlorethane and methylene chloride may be used to remove coatings, but care must be taken not to damage the board or components. Environmental restrictions may apply to the use of these solvents, so that alternatives may have to be used. Commercial compounds are also available which are designed specifically for this purpose.

Thermal Parting Thermal parting is a method using controlled low temperature heating and is best for the removal of thick coatings. Heat is applied directly to the coating which causes it to separate from the base material. If the coating is thick enough it can be peeled away from the base material.

Abrasion Abrasive jet equipment, similar to sand blasting, can be used to remove coatings that cannot be removed by solvents.

Plasma Etch The board is placed in a vacuum chamber and a low temperature plasma removes the coating. The plasma is created by exciting a gas with an RF (radio frequency) field. This method is useful for removing parylene [5.1].

SOLDER JOINT EXAMINATION

Overview Solder joints can be examined non-destructively by real time microfocus X-ray equipment. There are practical limitations to the resolution of this equipment and cracking and other defects with finer details may not be visible. Sectioning and optical microscopy are used successfully for diagnosing manufacturing problems and these techniques will work equally well in failure investigations if it is acceptable to section the board. Contaminants in the solder can be analyzed by SEM/EDS analysis.

As a consequence of the low melting point of solder, 182 °C (361 °F), cracked or broken solder joints will not survive very much exposure to post-impact fire. However, if the solder reflows during post impact fire, the appearance should be distinguishable from that of an undamaged PWB. Visually, reflow will cause some redistribution of the solder. Broken solder joints that have reflowed due to external heat may have additional voids. Additionally, SEM/EDS analysis may reveal contaminants trapped in the voids.

INSULATION RESISTANCE

Introduction Degraded insulation resistance can be the result of dendritic growth, contamination, and other problems.

Standard Procedure The military test procedures for moisture and insulation resistance are defined in MIL-STD-55110 and are based on the environmental test procedures in MIL-STD-202. Preconditioning and thermal cycling are required prior to the measurements which are then made at 100 Vdc. A minimum resistance of $500\text{ M}\Omega$ is required. The IPC has additional procedures which make use of two types of special PWB patterns designed specifically for test purposes.

Factors Insulation resistance measurements are extremely sensitive to environmental conditions. This is mostly due to the fact that polymeric materials absorb moisture over time and this can activate conductive contaminants on the substrate surface or in the bulk material of the substrate.

Humidity is the largest single factor and is responsible for most insulation-related problems. Insulating properties of PWB materials are extremely sensitive to relative humidity, especially if the PWB is already contaminated. On new boards the surface resistivity can change from 10^{15} to 10^{11} ohms/square when relative humidity changes from 30 to 90 percent [5.1]. The extreme sensitivity to moisture requires that laboratory tests be conducted under conditions simulating the actual field failure conditions.

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INSULATION RESISTANCE, Continued

Practical Procedures The measurement of resistances above 100 M Ω are extremely difficult to make on PWBs from field equipment, especially if there has been any exposure to fire fighting materials, water, and smoke. In addition, high voltage methods are not practical since they will cause additional component failures and measurement interactions. Fortunately, insulation resistance failures are usually well below 1M Ω , thus simplifying the measurement process.

Some guidelines for verifying insulation resistance problems:

1. The PWB should be exposed to humidity levels experienced in service before the measurements are made.
2. Circuit traces may need to be cut to isolate circuitry. This allows a single trace to be measured more accurately. Complex components or circuit areas may need to be removed to isolate the area of interest.
3. The PWB should be examined carefully with optical microscope or SEM to verify the physical source of the leakage or contamination.
4. Measurements should be made using low voltage techniques to avoid damage to components.

Precautions High resistance tests on PWBs removed from field equipment may need to be supplemented with tests on sample boards having the same trace patterns and components.

Use high series resistances in metering circuits and limit applied voltages to avoid damaging electronic components.

METALLURGICAL SAMPLE PREPARATION

Introduction Sample preparation consists of five basic steps which are outlined below. The parameters and materials for automatic polishing equipment are provided below [5.7]. Most of this information pertains to manual preparation as well. The principles of metallography and sample preparation methods are covered in [5.8].

PWB segments with plated-through-holes are usually mounted with carbide stops to assure that grinding will terminate before damaging the sample. The stops are removed before polishing. Other special accessories may also be used.

Sectioning Al_2O_3 Cutoff Wheel/Coolant.

Mounting Castable Media.

Grinding Table 5.3

Sic Grit Size	Time (secs)	Wheel Speed (rpm)	Pressure (psi)
180	Until all carbide stops are hit	300	35
600	60	300	35

Remove ring with carbide stops

Polishing Table 5.4

SiC Grit Size	Time (secs)	Wheel Speed (rpm)	Pressure (psi)
3 micron diamond compound/silk cloth/oil	240	250	30
1 micron diamond compound/red felt cloth/oil	60	250	30
Optional: Colloidal silica/wetted Imperial cloth	30	150	10

Etchants None.

SECTION D

REFERENCES

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CHAPTER 6

MICROELECTRONICS

OVERVIEW

Introduction Microelectronic devices are found everywhere in modern military aircraft. They control engines, weapons, communications equipment, and flight controls. The proliferation of microelectronic devices has ushered in a new era of military and commercial aircraft in which the conventional mechanical cockpit instruments have been replaced with electronic displays. This effect has forced mishap investigators to probe into the microelectronic devices which are operating "behind the scenes" to control the aircraft.

Fire and impact damage usually render microelectronic devices inoperable, but special techniques are available to obtain clues or recover data they may contain.

The investigation can focus on microelectronic devices for several reasons:

1. They may be suspected of failing and playing a causal role in the mishap.
2. Microelectronic devices that remain operational after a mishap may provide clues as to what equipment on the aircraft was functioning properly prior to the mishap.
3. They may contain data about the state of the aircraft prior to or during the mishap. This is becoming increasingly more likely as the use of non-volatile memory devices increases. This area of analysis matured somewhat in the late 1980s, and is covered in Section C.

The type and complexity of microelectronic devices may be somewhat overwhelming to the mishap investigator and laboratory analyst. The devices themselves and analytical techniques used to evaluate them are the subject of volumes of material previously published [6.1-6.5]. The purpose of this chapter is to provide a basic understanding of the construction technologies and the more accessible analysis procedures.

OVERVIEW, Continued

Contents This chapter is divided into four sections.

Section	Title	Page
A	Background	233
B	Failure Characteristics	249
C	Failure Analysis Procedures	269
D	References	291

SECTION A

BACKGROUND

INTEGRATED CIRCUIT MANUFACTURING

Overview Integrated circuit (IC) fabrication is a complex combination of processes which has evolved since the invention of the transistor in 1948. A brief overview of some of the processes is presented here to help orient the mishap investigator. IC fabrication is covered in detail in [6.6].

Contents There are nine articles in this section covering three major topics: construction, fabrication processes and background information.

Construction

- Overview of IC Manufacturing
- Anatomy of an Integrated Circuit

Fabrication Processes

- Integrated Circuit Processing
- Wafer Processing
- Die Attach
- Wire Bonding
- Packaging

Background Information

- Materials
- Military Standards

OVERVIEW OF IC MANUFACTURING

Introduction A brief overview of the basic steps in IC manufacturing is presented in the following discussions.

Silicon Most ICs are made from silicon, the most abundant material in the earth's crust. Silicon is processed from sand, purified, and cast into rods that have a polycrystalline structure. This form of silicon is called polysilicon or just "poly".

Wafers Polysilicon is processed in melting furnaces to form single crystals of silicon up to several inches in diameter. These large crystals are cut into thin circular wafers. A typical wafer is 100 mm in diameter and about 0.5 mm thick.

Wafer Fabrication Multiple copies of an IC pattern are reproduced on a single wafer. All of the pattern copies, called dies, are formed simultaneously. This process is called wafer fabrication, or just "fabrication".

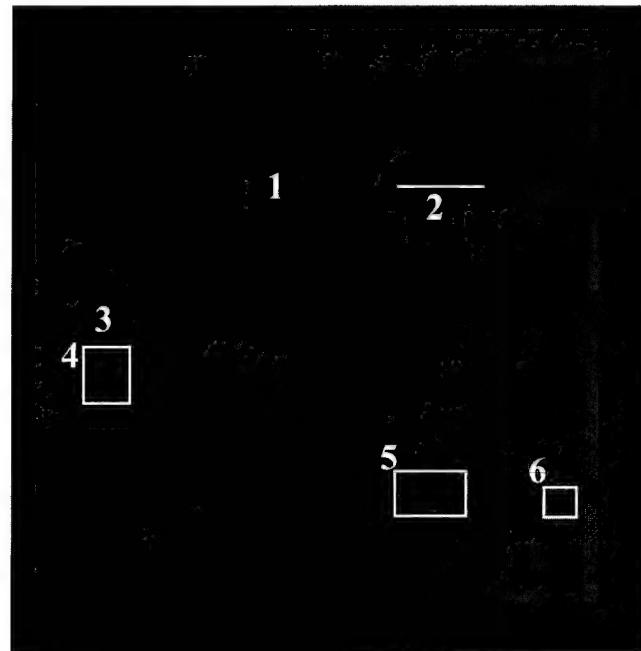
Die Separation When wafer fabrication is complete the dies are cut from the wafer using a special saw. One wafer may make over a hundred dies, depending on the size of the dies and the wafer.

Packaging The last step in the production process is packaging. Molded plastic, ceramic, and metal packages are all used.

Testing Electrical testing is conducted during wafer fabrication, and before and after packaging.

ANATOMY OF AN INTEGRATED CIRCUIT

Example Figure 6.1 is an optical microphotograph of a simple bipolar integrated circuit (IC) die. Some of the physical features are described briefly below. These features are covered in more detail later in this section.



Capacitor Large areas of metallization are used to form one plate of an IC capacitor.

Aluminum Traces Aluminum traces formed during metallization are used to interconnect circuit components. They have a dark, grainy appearance in the photo. The marked trace (2) connects to the top surface of the capacitor.

Bonding Pads The circuit input and output terminals are provided with bonding pads located along the edges of the die. These facilitate the connection of bond wires.

Bond Wires These wires are attached to the bonding pads and connect the circuit to the package leads. Aluminum wires are the most common, but gold and other materials are also used.

Bipolar Transistor A typical bipolar transistor is shown. The three terminals are the collector, emitter and base (left to right).

Alignment Marks The alignment of all the patterns is accomplished with these marks located on the outside edge of the die.

INTEGRATED CIRCUIT PROCESSING

Silicon Wafers IC processing starts with silicon wafers. Wafers are made by melting polysilicon in furnaces to form single crystals of silicon up to several inches in diameter. The crystals are cut into wafers, a typical wafer being 100 mm in diameter and about 0.5 mm thick.

A single wafer can be processed to make over a hundred copies of an IC at one time. The number of copies of an IC that fit on a wafer depends on the size of the pattern and wafer. Each copy of the pattern is called a chip or die. The chips are separated by sectioning the wafer with a special type of saw.

Wafer Processing

The three basic steps in IC processing are:

- layering
- patterning
- doping

The formation of circuits on the wafer involves a complex sequence of these steps and some variations may be needed at each stage. The exact sequence depends on the type of IC and its complexity.

Layering

Thin layers of different materials are added to the wafer surface. Silicon dioxide is one example. The layers can function as insulators, semiconductors, or conductors. A typical layer is 0.75 microns thick. Two special types of layers are described below. They are:

1. *Metallization* is a conductive layer which connects components together to form a circuit. It is usually formed by depositing a layer of aluminum over an insulating layer. Holes in the insulating layer allow the metallization to contact specific areas of the circuit components in the layers below.
2. *Passivation* is an insulating layer of silicon dioxide or silicon nitride applied on top of the last metallization layer. It protects the circuit from contamination and prevents damage to the metallization.

Both metallization and passivation materials are encountered during mishap investigations.

Continued on next page

INTEGRATED CIRCUIT PROCESSING, Continued

Patterning In patterning, selective portions of a metallization or passivation layer are removed to expose the layer below. For example, a passivation layer may be patterned so that metallization can be connected to a transistor below.

Doping Dopants are added to the wafer to selectively change the electrical properties needed to form transistors, resistors, and diodes. Doping takes place through the holes patterned in the surface layer. Two techniques are used in doping. They are:

1. *Thermal Diffusion* is performed by heating the wafer and exposing it to vapors containing the desired dopant. Atoms of the dopant diffuse into the wafer creating regions with altered properties.
2. *Ion Implantation* is a method where the dopant atoms are accelerated electrically and "shot" into the wafer.

Examples Figure 6.2 shows an SEM microphotograph of a bipolar transistor on an IC.

Figure 6.3 is a diagram of the cross-section of the transistor and illustrates several of the fabrication features. N- and P-type doped regions are used to construct the collector (N), base (P), and emitter (N) regions. The diagram shows an NPN transistor.

Continued on next page

INTEGRATED CIRCUIT PROCESSING EXAMPLES

Figure 6.2 An SEM microphotograph of a bipolar transistor on an IC. Magnification: about 500X.

1. Metallization
2. Collector
3. Emitter
4. Base

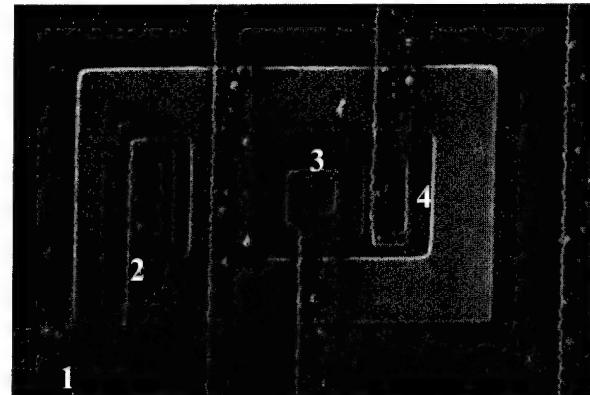
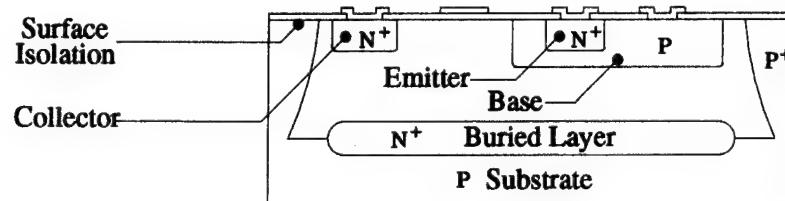


Figure 6.3 The cross section and fabrication features of a bipolar transistor.



DIE ATTACH PROCESS

Overview Die attachment is the process of setting the finished IC die into a package. The primary function of the process is to provide the mechanical mount for the die, but there may be requirements for specific levels of thermal and electrical conductivity as well.

Die attach problems are of interest to IC testing laboratories, and can also be of interest during mishap investigations. A more detailed discussion of the materials and processes can be found in [6.7].

Eutectic Bond A gold-silicon eutectic is used to attach the die. It contains 3% silicon by weight and has a melting point of 363°C (685°F). It is common in hermetically sealed military packages. In one process the eutectic alloy is formed by coating the package with gold and placing the die in the package at an elevated temperature. The alloy forms as the silicon die touches the gold.

Glass Glass is used in commercial hermetically sealed packages where electrical connection to the substrate is not needed. The method is to heat the package and glass, and then set the die into the melted glass.

Polymer Adhesive Polyamide and epoxy formulations are used. They are usually filled with silver to provide electrical conductivity.

Solder Used with metal "can" devices when heat must be conducted from the die to the case. Common formulations are 95% lead/5% tin and 65% tin/25% silver/10% antimony.

WIRE BONDING

Overview	Interconnect wires are needed to electrically attach the die to the package leads or to interconnect the various devices in a hybrid IC.
Methods	There are three basic methods used for bond wire attachment. They are: <ol style="list-style-type: none">1. Thermocompression bonding uses a combination of heat and pressure to form the bond. It is commonly used with gold wire, which can be bonded to either gold or aluminum metallization. A ball-shaped terminal is usually found on one end of the bond wire when this process is used. The wire and metallization are both heated to accomplish the bonding.2. Ultrasonic bonding is a low temperature bond made by vibrating the bonding tool against the metallization at a frequency of 20 - 60 kHz. This process is commonly used with aluminum or gold metallization. In ultrasonic bonding, both ends of the wire are usually shaped like a wedge.3. Thermosonic bonding uses heat and ultrasonic energy to form the bond. The temperatures are lower than those used for thermocompression bonding.
Lead Frame	The lead frame contains a set of formed leads which provide the transition of electrical connections from the die to the outside world. The lead frame may also provide the mounting surface for the die, and help support the packaging process. Bond wires connect individual parts of the lead frame to the appropriate points on the die to complete the electrical connections.
Materials	Alloys of aluminum and gold are the most common materials used for bond wires. Alloys provide better mechanical properties than the pure metals. Table 6.2, found later in this section, lists the most common bond wire materials.

PACKAGING

Overview

ICs are made in a wide variety of package styles. The particular package depends on the complexity and number of pins, environmental requirements, and other factors. The military mishap investigator will generally encounter a wide range of package styles because of the range of ages of aircraft presently in service. A few of the common package styles are described in the following discussion. These include:

- Molded Plastic Package
- Ceramic Package
- Hybrid IC Package
- Metal Case Power Transistor

Molded Plastic Package

The basic construction of a molded plastic IC package is shown in Figure 6.4. The die is attached to a center pad (called the die attach pad) of the lead frame. Bond wires connect the lead frame fingers to the die. The die and lead frame are encapsulated in a thermosetting polymer by transfer molding. Dual-In-Line Packages (DIPs) and surface mount packages, such as the Plastic Leadless Chip Carrier (PLCC) and many others, can be made using the same basic method.

Ceramic Package

One type of ceramic package is the Ceramic Dual-In-Line Package, or CERDIP, shown in Figure 6.5. The base and lid of the package are made of ceramic, which has been coated with low-temperature glass. The lead frame and die are attached to a well in the base. The lid is attached after wire bonding. The package is sealed by heating process which melts the glass coatings of the lid and base and seals them to the leads. This produces a hermetically sealed package.

Hybrid Package

A common package style for hermetically sealed hybrid ICs is the metal bathtub-type package, shown in Figure 6.6. A bathtub-shaped container is drawn and punched for side leads and welded or soldered to a base plate. The dies and other components of the hybrid are mounted on a ceramic substrate, and then attached to the base of the bathtub container. Bond wires are attached to leads that are brought out through hermetic glass-to-metal seals. A flat metal lid is then welded to the top to form a hermetic seal.

Metal Case Power Transistor

A metal case commonly used for power transistors is the TO-3 style case shown, in Figure 6.7. The finished die is mounted on a heat spreader in the case, and bond wires are attached. A metal lid is welded over the base to form a hermetic seal. The case is one lead of the three terminal device. This is usually the collector terminal on transistors. The remaining two leads are brought out through hermetic glass-to-metal seals.

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PACKAGING EXAMPLES

Figure 6.4 The basic construction of a molded plastic IC package.

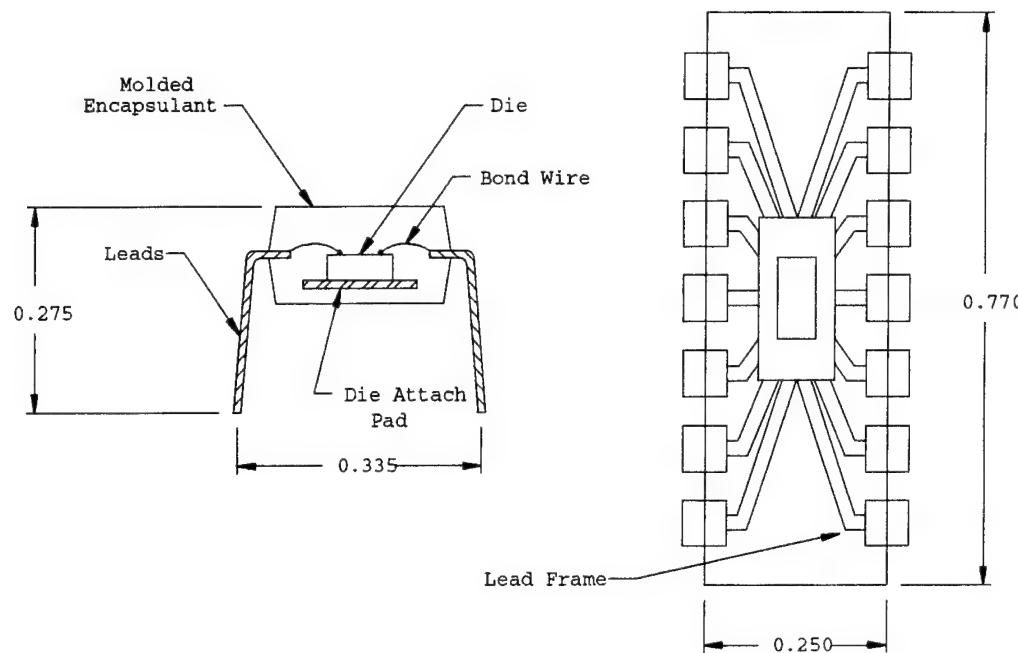
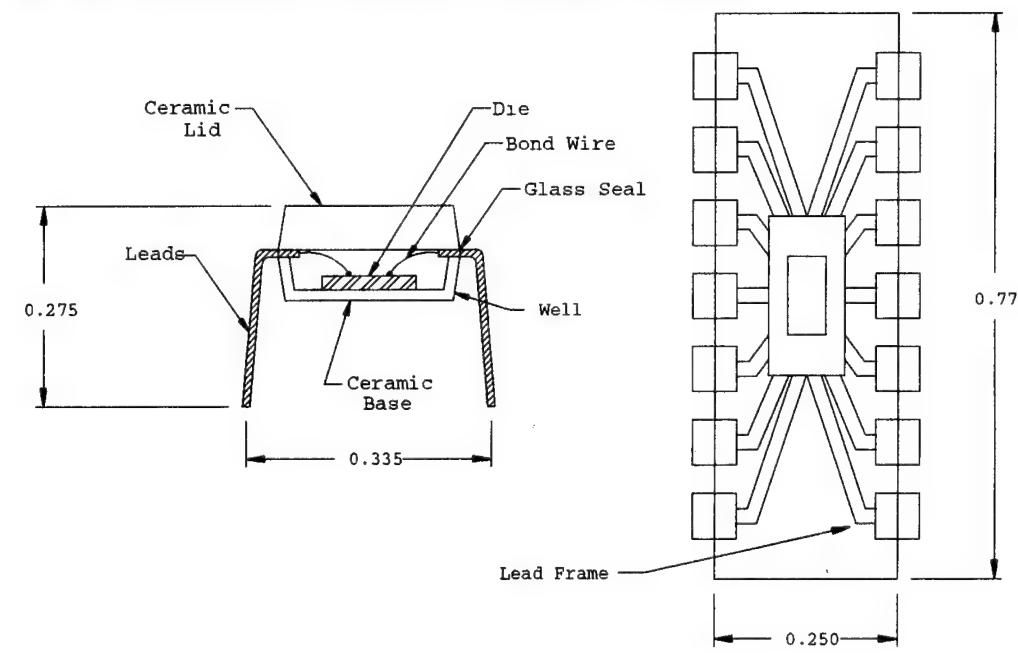


Figure 6.5 The basic construction of a ceramic IC package (CERDIP).



Continued on next page

PACKAGING EXAMPLES, Continued

Figure 6.6 The basic construction of a hybrid IC package.

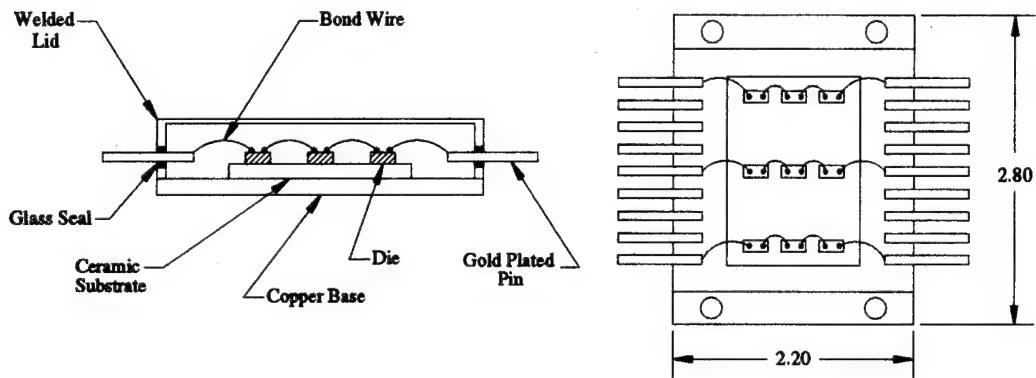
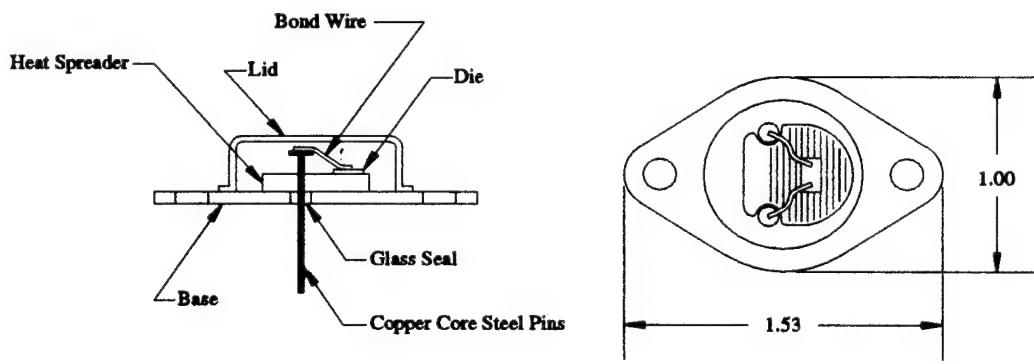


Figure 6.7 The basic construction of a typical metal case transistor package.



MATERIALS

Overview

A comprehensive list of all the materials used in military ICs would include several hundred polymers, ceramics, and metal alloys. This material has been condensed and adapted to help familiarize the investigator with the number and types of materials involved. Detailed information can be found in [6.7]. The material is organized in the following tables:

IC Layering Materials	Table 6.1
Bondwire Materials	Table 6.2
IC Package Materials	Table 6.3
Composition of Lead Frame Alloys	Table 6.4

Continued on next page

MATERIALS, Continued**Table 6.1** Materials used for IC layer fabrication.

Layers	Materials
Insulation	Silicon Dioxide Silicon Monoxide Silicon Nitride
Semiconductors	Silicon Polysilicon
Conductors	Aluminum Aluminum/Silicon Aluminum/Copper Nichrome Gold Tungsten Titanium Molybdenum

Table 6.2 Aluminum and gold alloys are the most commonly used bond wire materials. They are used in standard sizes between 0.02 mm (0.7 mils) and 0.5 mm (20 mils). Thicker wires are used on higher power devices.

Bondwire Materials	
Aluminum	+1% Silicon +0.5% to 1% Magnesium
Gold	Beryllium doped: 5-10 ppm Copper doped: 30-100 ppm
Silver	N/A
Palladium	N/A

Continued on next page

MATERIALS, Continued**Table 6.3** IC packaging materials.

Plastic Packages	Base Material
	Epoxies
	Silicones
	Urethanes
	Phenolics
	Acrylics
	Diallyl Phthalate
	Polyesters
	Polyimides
	Fillers
Ceramic Packages	Silica
	Calcium Carbonate
	Alumina (Aluminum Oxide)
	Carbon Black
	Base Materials
	Alumina (Aluminum Oxide)
	Silica
	Glass
	Beryllia (Beryllium Oxide)
	Aluminum Nitride
Metal Packages	Other Materials
	Organic Binders
	Solvents
	Plasticizers
	Iron-Nickel-Cobalt Alloy (ASTM-F-15 or MIL-I-23011)
	Copper
	Molybdenum
	Copper-Silver
	Steel

Continued on next page

MATERIALS, Continued**Table 6.4** The nominal composition of lead frame alloys.

Alloy Group	Designation	Nominal Composition, Net%
Cu-Fe	C19400	2.35Fe-0.03P-0.12Zn
	C19500	1.5Fe-0.8Co-0.05P-0.6Sn
	C19700	0.6Fe-0.2P-0.04Mg
	C19210	0.10Fe-0.034P
Cu-Cr	CCZ	0.55Cr-0.25Zr
	EFTEC 64T	0.3Cr-0.255Sn-0.2Zn
Cu-Ni-Si	C7025	3.0Ni-0.65Si-0.15Mg
	KLF-125	3.2Ni-0.7Si-1.25Sn-0.3Zn
	C19010	1.0Ni-0.2Si-0.03P
Cu-Sn	C50715	2Sn-0.1Fe-0.03P
	C50710	2Sn-0.2Ni-0.05P
Other	C15100	0.1Zr
	C15500	0.11Mg-0.06P
Fe-Ni	ASTM F30 (Alloy 42)	42Ni-58Fe
Fe-Ni-Co	ASTM F15 (Kovar)	29Ni-17Co-54Fe

MILITARY STANDARDS

Military Standards The primary military standard for ICs is MIL-STD-883 [6.8], "Test Methods and Procedures for Microelectronics." It includes mechanical, electrical and environmental test requirements for qualification of military microelectronic devices. Other standards cover semiconductor devices, in general. A listing of most of the standards related to semiconductor and microelectronic devices is shown in Table 6.5.

Table 6.5

Document Number	Military Document Title
MIL-STD-883	"Test Methods and Procedures for Microelectronics"
MIL-STD-785	"Reliability Program for Systems and Equipment Development and Production"
MIL-STD-975	"NASA Standard Electrical, Electronic and Electromechanical Parts List"
MIL-STD-1547	"Parts, Materials and Processes for Space and Launch Vehicles, Technical Requirements for"
MIL-STD-1562	"List of Standard Microcircuits"
MIL-M-38510	"Microcircuits, General Specifications for"
MIL-STD-19500	"Semiconductor Device, General Specification for"

SECTION B

FAILURE CHARACTERISTICS

OVERVIEW

Introduction This section covers the physical features that can be observed when examining microelectronic devices during a mishap investigation.

Scope Microelectronic devices have complex physical structures; the range of failure analysis methods required is too broad to be covered in this handbook. Instead, failure characteristics and their associated physical damage are covered here, since these characteristics are most likely to survive impact and fire damage.

A whole array of physical features associated with manufacturing problems has been intentionally avoided. This is because these characteristics are difficult to diagnose, and usually will not survive the mishap.

Discussion The investigator is often faced with analyzing damaged components. Many microelectronic device failures cause distinct structural damage in isolated locations of the device. This damage may survive brief exposure to temperatures up to the melting points of the materials involved. Since the melting point of silicon (of which most devices are fabricated) is 1410 °C (2570 °F), there is a significant opportunity for this damage to survive exposure to post-impact fire. Further, the type of damage caused by post-impact fire alone affects the entire device rather than isolated areas.

Unfortunately, severe mechanical damage from impact frequently renders the device useless, from an analysis standpoint. The difficulty is that the numerous secondary electrical failures and fire that often occur on impact may mask any evidence of pre-mishap failures. On the other hand, equipment is occasionally de-energized on impact, which helps preserve the state of the internal devices.

Contents

- Overvoltage
- Overcurrent
- Corrosion
- Wire Bond Failure
- Impact Damage
- Thermal Damage
- Altered Electrical Characteristics

OVERVOLTAGE

Observation	Short duration overvoltage events can cause microelectronic device failures and usually result in some physical damage.
Cause	Overvoltage conditions can be caused by a number of events which are external to the device in question. Some of the most common conditions are: <ul style="list-style-type: none"> • electrostatic discharge (ESD) • supply voltages transients • electromagnetic coupling between signal cables • connector and printed wiring board failures
Mechanism	There are two basic mechanisms for overvoltage failures. They are: <ol style="list-style-type: none"> 1. The voltage can cause breakdown of the insulating material layers used in device construction. 2. The voltage permanently alters the characteristics of P-N junctions. This is usually caused by exceeding the reverse breakdown voltage.
Precautions	None.
Discussion	Overvoltages that cause device failures also cause some physical damage to the device. The amount of damage depends on how much energy is available at the fault site. It also depends on how the device is used, and the voltage and current capability of the power supply. <p>Failure modes of transistors are well known, and the mode of failure can usually be determined from the location of the damage. A detailed discussion of these failures can be found in [6.9].</p>
Data	The dielectric strength of silicon dioxide is about 1000 V per micron. The thickness of the oxide layer depends on the application and can range from 100 Angstroms (10^{-2} micron) to over 1 micron. One Angstrom is 10^{-10} meters or 10^{-4} microns. The gate oxide of a CMOS transistor on an IC is about 100-300 Angstroms thick (0.01 to 0.03 microns). Interlayer insulation is on the order of 1000 Angstroms (0.1 micron) in thickness.

Continued on next page

OVERVOLTAGE, Continued

Analysis Analysis is conducted by optical microscopy and SEM.

Examples Figure 6.8 shows damage caused by overvoltage stress between the base and emitter junction of a bipolar transistor. A resistive short exists between the junctions.

Figure 6.9 is an SEM micrograph of the same site at higher magnification. The hole is a "punch through" site showing where the insulation failed.

Continued on next page

OVERVOLTAGE EXAMPLES

Figure 6.8 Overvoltage failure at the base - emitter junction of a bipolar transistor. Magnification: about 460x.

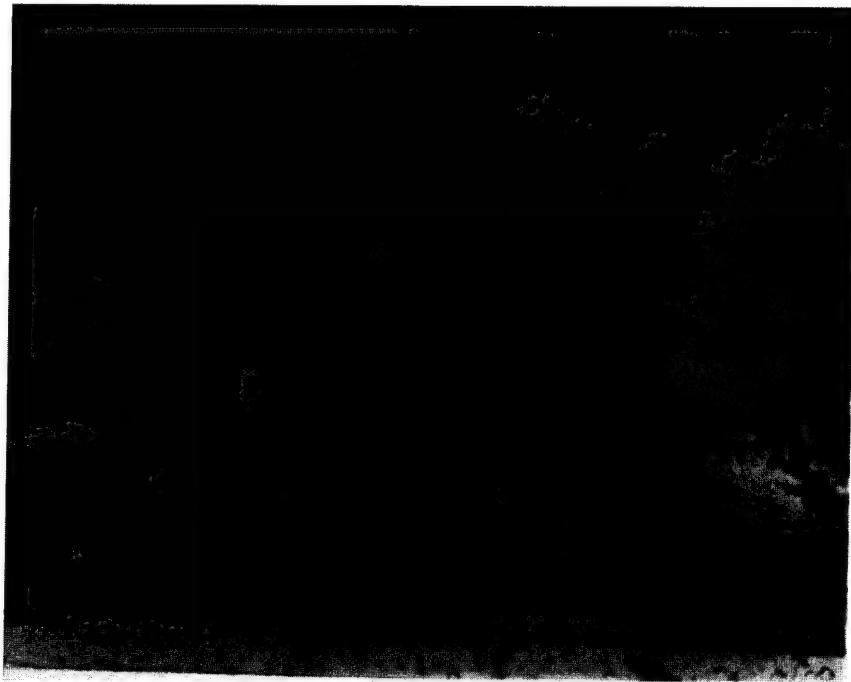


Figure 6.9 SEM photograph of "punch through" site. Magnification: about 4500X.



OVERCURRENT

Observation A common failure mode of bond wires and device metallization is overcurrent failure, which tends to melt the conductor material.

Cause Overcurrent failures are usually caused by electrical short circuits in load devices or cables. Overcurrent failures in microelectronic devices are usually secondary failures, which can be used to determine the primary failure mechanism and location.

Mechanism Overcurrent conditions can produce sufficient heat to melt or vaporize bond wires and metallization. Excessive heating occurs when the current density of the wire or trace is exceeded. The thermal power is expressed in watts as $P=I^2R$.

Precautions None.

Discussion Both gold and aluminum bond wires exhibit overcurrent failures in similar ways. Both materials are excellent thermal conductors and the attachments at the end will help cool the ends of the wires. As a result, the highest temperature, and most common failure location, will be near the mid span of the wire.

Gold wires will usually form a ball at the end and this is the key feature to look for. Aluminum wires usually melt and separate while taking on a wrinkled appearance. Aluminum does not usually form a ball at the failure site.

The magnitude and duration of the overcurrent will determine whether the bond wire or metallization will melt first. Very short duration current pulses will tend to melt the metallization first because it has lower cross section area and higher resistance than the bond wire. As the pulses becomes longer in duration and lower in magnitude, failure of the wire becomes more prevalent. This is because the thermal coupling to the bulk of the die becomes effective in cooling the aluminum metallization [6.10].

Continued on next page

OVERCURRENT, Continued

Data The melting point and thermal conductivity of some materials used for bond wire and metallization interconnects are listed in the table below for reference:

Material	Melting Point in °C	Thermal Conductivity in W/cm·°C
Aluminum	660	2.18
Gold	1063	2.96
Silicon	1410	0.84
Tungsten	3410	1.99

An approximate formula for the fusing current of an infinitely long 99% aluminum, 1% silicon wire is $I=0.4D$, where D is the wire diameter in mils. This expression assumes that the length of the wire $L > 100D$, and this is a good approximation for many devices.

Analysis Melting of conductors or device metallization will normally be visible at magnifications below 1000X, so that optical microscopy and SEM may both be used effectively. The SEM is preferred for its depth of field.

Example Figure 6.10 shows a switching power transistor which failed due to overcurrent. Note that the bond wires are melted in the middle.

Figure 6.11 shows an operational amplifier in which the output stage failed on overcurrent. Note the melted metallization.

Continued on next page

OVERCURRENT EXAMPLES

Figure 6.10 Figure 6.10 shows the ball-shaped ends of bond wires melted during an overcurrent. Magnification: about 6X.

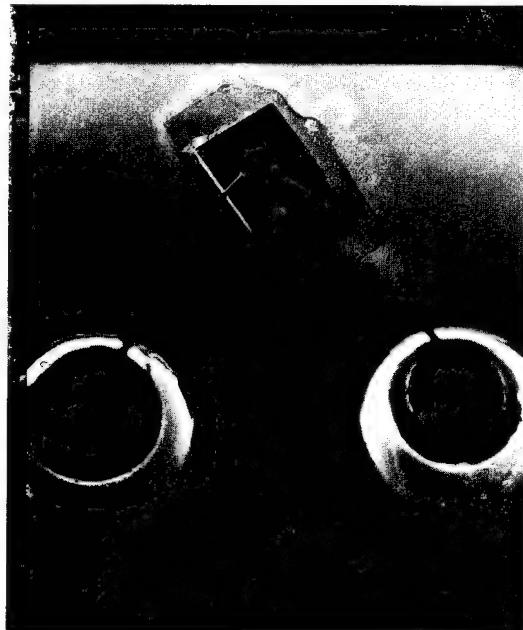
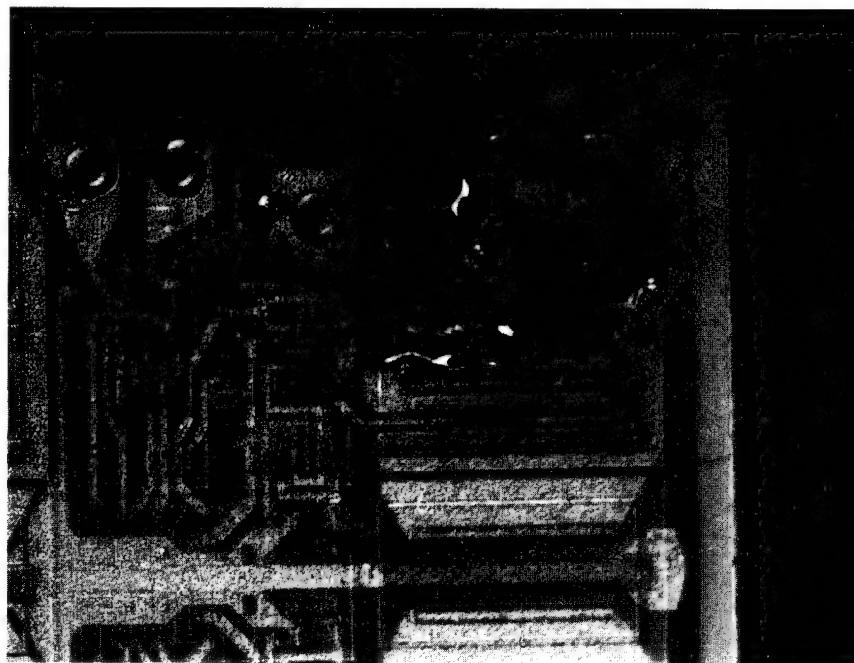


Figure 6.11 Figure 6.11 shows melted aluminum metallization on the output transistor of an operational amplifier. Magnification: about 60X.



CORROSION

Observation	Corrosion causes the physical degradation of metals. It often leads to electrical and mechanical failures in microelectronic devices [6.7].
Cause	Corrosion requires a galvanic couple, corrosive contaminant, and moisture for activation.
Mechanism	<p>Corrosion is the destructive attack of metals by a chemical reaction between the metals and a corrosive agent in the presence of moisture. Contaminants can come from several sources:</p> <ul style="list-style-type: none">• cleaning fluids used prior to packaging• package leaks• human contaminants, such as saliva and perspiration <p>The result is usually the same - destruction of the metal. This typically results in high resistance electrical connections and mechanical failures. Operating voltages present in the device usually accelerate the corrosion process. However, these voltages are not necessary to cause catastrophic failures.</p> <p>Moisture can enter the device during the packaging process. It can also enter the package after assembly, from failures caused by mishandling, vibration and thermal stress. Failure of lid seals and cracking of glass-to-metal connection seals are two packaging defects that can result in moisture intrusion.</p> <p>Moisture can be sealed inside the device package during assembly or may be generated from material outgassing after sealing. Outgassing is usually a problem associated with molded plastic packages.</p>
Precautions	None.
Discussion	Corrosion inside the microelectronic device package usually occurs where exposed metal is present. This includes the bond wires, bonding pads and any exposed metallization. In addition, some contaminants will pass through the thin glass layer and attack the underlying metallization.
	Corrosion outside the device package usually occurs on or near metal surfaces, especially on leads, metal packages, and glass-to-metal seals.

Continued on next page

CORROSION, Continued

Data	<p>Elemental analysis typically reveals the presence of ionic contaminants in the products of aluminum metallization corrosion.</p> <p>Attack by saliva results in a corrosion product containing aluminum, potassium, chlorine, sodium, some calcium, and a trace of magnesium.</p> <p>Attack by perspiration sometimes contains zinc, which is a common ingredient in most antiperspirants.</p> <p>Another source of corrosion is phosphorous in the glass passivation that combines with moisture in the package. If the phosphorous and moisture levels are high enough, then phosphoric acid can form and attack the device. Moisture levels above 5000 ppm are usually needed for this type of corrosion.</p> <p>Cosmetics are also a possible source of contamination during manufacturing. Iron and aluminum have been found in mascara. Facial powder may contain titanium, iron, magnesium, aluminum, and potassium. Sodium and chlorine are usually not found in cosmetics [6.11].</p>
Analysis	Analytical techniques include optical microscopy, SEM, and EDS.
Examples	None.

WIRE BOND FAILURE

Observation	Mechanical and electrical failure of bond wires can be observed in microelectronic device failures. Detached bonds, shorts, corrosion, and overcurrent failures may all be observed as failure indicators.
Cause	Bond wire failures can be caused by contamination, electrical overstress, or improper bonding parameters (pressure, temperature, time).
Mechanism	<p>Contamination of the IC surface can prevent proper bonding of the wire to the bond pad.</p> <p>Electrical overload can cause local melting of the bond wire.</p> <p>Improper bonding parameters can cause incomplete bonding, mechanical fractures, and promote conditions favorable for metallurgical failures. The resulting bond can fail mechanically from vibration, shock, and temperature cycling in normal operation.</p>
Precautions	None.
Discussion	<p>Gold bond wires attached to aluminum metallization can develop a condition called "purple plague". This is caused by the formation of AuAL_2, which is a gold-aluminum intermetallic compound.</p> <p>The formation of gold-intermetallic compounds is essential to making a good bond. As the AuAL_2 intermetallic forms, it expands in the region between the gold wire and the aluminum, degrading the mechanical strength and electrical contact of the bond.</p>
Data	The five gold-aluminum intermetallics are listed in Table 6.6.

Continued on next page

WIRE BOND FAILURE, Continued

Table 6.6 Gold-Aluminum Intermetallic Compounds.

Compound	Formation Temperature	Color
Au_5AL_2	100 °C	Tan
Au_2AL	50 °C	Metallic Gray
AuAL_2	150 °C	Deep Purple
Au_4AL	150 °C	Tan
AuAL	250 °C	White

Analysis The SEM, in conjunction with EDS, is the best tool for examining wire bonds. Backscattered electron (BSE) imaging can be helpful in identifying the intermetallics.

Examples None.

IMPACT DAMAGE

Observation Mishaps resulting in aircraft breakup and ground impact can cause several distinct forms of damage to microelectronic devices.

Cause Impact damage is caused by a variety of forces that occur during a mishap. The fragile nature of microelectronic devices makes them susceptible to damage from shock. Pure shock loads are just one type of loading that can occur. Crushing, bending, and shearing forces may also be present.

Mechanism Unlike some of the other failure characteristics discussed in this chapter, impact damage to microelectronic devices can manifest itself in a variety of ways. Some of the more common indications are described below:

1. Bond and lead wire deformation occur when the device is subjected to a high-g shock. The mass of the wire or lead cause them to deform in the direction of the impact.
2. Die fracture can be the result of shock loads or bending stresses applied from outside the device. The silicon die of a microelectronic device is brittle; it will crack easily if bending forces are applied. Under normal circumstances the package and printed wiring board isolate the die from these forces. The extreme forces encountered during impact, however, may cause die fractures.
3. Package damage can be caused by crushing, scraping, shock, and bending forces that occur during breakup and impact. Ceramic packaged devices are extremely brittle and are subject to fractures from impact. In contrast, metal-cased transistor packages can be dented and deformed, while leaving the device operational.

Precautions Microelectronic devices are extremely fragile. They can be physically damaged at any time during the multiple impacts that occur in serious mishaps. This usually limits the useful information that can be obtained by an examination of the impact damage alone.

Some of the damage discussed in this section may be caused by other mechanisms. For example, die fractures can be caused by thermal shock, as well as several other mechanisms. The investigator must correlate observations with other data before concluding that impact damage alone is the cause of a specific physical feature.

IMPACT DAMAGE, Continued

Discussion The specific type of damage caused by impact depends on several factors. These include:

1. Device size. Larger, heavier devices will generally be more susceptible to damage under the same conditions than lighter devices.
2. Package style. Ceramic packages are more brittle than plastic and will chip and crack from shock loads.
3. Mounting. Through-hole mounting is more rugged than surface mount technology. Some surface mount devices have been sheared off the printed wiring boards from impact shock loads.

Data None.

Analysis Since microelectronic devices are usually mounted on printed wiring boards, a careful visual examination is always the first step. At this stage, damage to device packages and external leads should be apparent.

Low magnification (10-100x) optical microscopy will be useful when there is significant damage to the package.

Decapsulation or delidding of the package will be necessary to verify internal damage. Optical microscopy at higher magnifications may be needed. It may also be necessary to section the printed wiring board so that it can be handled conveniently under the microscope.

Examples Figure 6.12 shows ceramic packaged memory ICs mounted on a printed wiring board. The board was removed from an F-4 which was involved in a mishap. The lids on the ceramic packages sheared off during impact. The ICs are 4164 MOS dynamic memory devices. A thin polyimide coating covering the die is visible. It was used on early technology memory devices to reduce "soft" memory errors.

Figure 6.13 shows a damaged metal cased power transistor. The device is a 2N5684 50 A PNP power transistor removed from a power amplifier on an F-111.

Continued on next page

IMPACT DAMAGE EXAMPLES

Figure 6.12 Damaged memory ICs removed from an F-4. Magnification: about 2X.

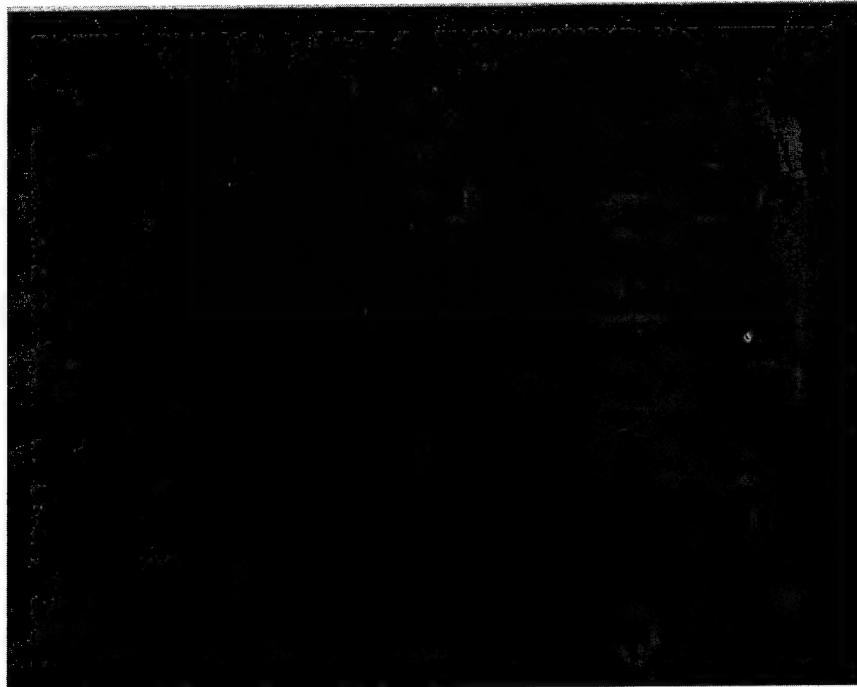
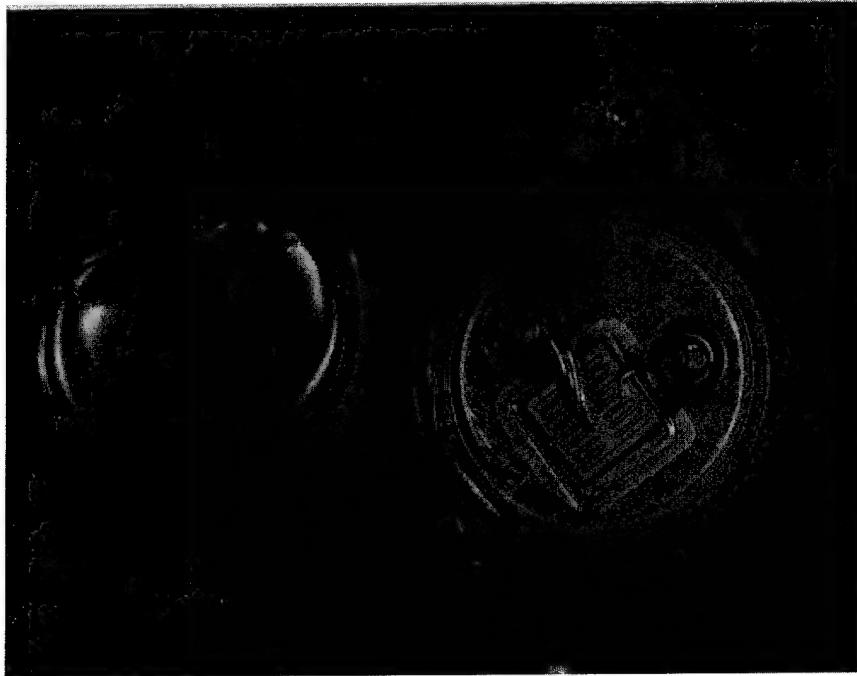


Figure 6.13 Damaged power transistor removed from an F-111. Magnification: about 2X.



THE THERMAL DAMAGE

Observation Thermal damage manifests itself in microelectronic devices in a number of related ways.

Cause Sources of thermal damage include post-impact fire, cooling system failures, and overheating of external electrical equipment.

Thermal damage is primarily the result of gross exposure of the device to elevated temperatures which may occur during post-impact fire.

Mechanism The junctions of silicon microelectronic devices are formed by doping regions of the bulk silicon. Junction characteristics are altered at elevated temperatures, causing the device to fail. This occurs in the range of 150 to 250 °C (302 to 482 °F) for silicon. If the device is not energized the condition is reversible and does not physically damage the device.

Physical damage will occur if the device is energized. Junction failures will generally lead to catastrophic currents. The resulting damage usually causes an avalanche of secondary failures that destroy the device.

Other events may occur as the temperature is elevated above 250 °C (482 °F). These include:

1. Various gold/aluminum eutectic compounds begin to form at temperatures of 150 to 250 °C (302-482 °F). Thus, the interface of the gold bond wires and the aluminum metallization may be altered at these temperatures
2. A gold/silicon eutectic compound is used to attach the die to hermetically sealed ceramic packages. The eutectic forms at about 370 °C (698 °F). Temperatures of 225-275 °C (437-527 °F) should not lead to significant degradation of the bond.
3. An aluminum/silicon eutectic compound forms at about 570 °C (1058 °F) at the interface between the metallization and the bulk silicon of the die. However, temperatures of 450-500 °C (842-932 °F) for short periods generally will not result in the formation of the eutectic.

Precautions The interpretation of thermal damage is not well established. This is partly due to the fact that most of the mechanisms are time and temperature dependent. Many combinations of these variables may result in similar physical damage to a device.

Continued on next page

THERMAL DAMAGE, Continued

Discussion This discussion excludes thermal damage in specific areas of a transistor or IC caused by electrical failures.

Data Temperatures for damage of materials in microelectronic devices are listed in Table 6.7.

Table 6.7 Temperatures for damage of materials for microelectronic devices.

Temperature (°C)	Phenomenon
150-250	Semiconductor actions fails
150-250	Gold/Aluminum eutectic forms
370	Gold/Silicon eutectic forms
570	Aluminum/Silicon eutectic forms
660	Aluminum Melts
1063	Gold Melts
1410	Silicon Melts

Analysis Analysis is best conducted by optical microscopy and SEM. Eutectics can be identified by SEM in BSE mode or by EDS since they have a composition that is distinctly different from the standard materials.

Examples None.

ALTERED ELECTRICAL CHARACTERISTICS

Observation	Altered electrical characteristics are frequently encountered during mishap investigation. They may be observed during testing of equipment and on isolated devices.
Cause	Changes in microelectronic device characteristics can be caused by failures that occurred prior to the mishap, or by thermal and mechanical damage during the mishap.
Mechanism	A variety of manufacturing, handling, and circuit conditions can cause degradation of device characteristics, or total failure during operation. These include: <ul style="list-style-type: none"> • inherent contamination • package integrity failures • wire bond defects • die attach problems • device fabrication problems Mechanical shock and fire associated with a mishap can also cause numerous types of device failures, with distinctly different causes and failure conditions.
Precautions	Electrical testing should be conducted with caution. Curve tracers and other test equipment can damage microelectronic devices and destroy important information. Further, partially damaged devices can be destroyed at much lower levels of electrical stress than good devices. Extreme caution should be exercised during the first stages of electrical testing.
Discussion	Electrical testing should be conducted prior to destructive tests to document the condition of the device.
Data	None.
Analysis	Only limited electrical testing can be accomplished when a microelectronic device has suffered much physical damage. <p>Test methods depend on the type of device and the extent of damage. There are basically three types of testing which can be done:</p>

Continued on next page

ALTERED ELECTRICAL CHARACTERISTICS, Continued

Analysis (Cont'd)

1. Basic electrical testing may be accomplished using an ohmmeter to identify device failures, shorts, and open circuits in bond wires. This type of testing is useful for all types of devices.

2. Curve tracer testing may be used to determine characteristics of diodes, transistors, and simple active components. This is most useful on discrete devices, but can be used on ICs where junctions or transistors can be isolated for testing.

3. Complete electrical performance testing of ICs may be accomplished using automatic test equipment. The test equipment is preprogrammed to provide a series of electrical inputs, called test vectors, and compares the output to the recorded characteristics of ideal devices.

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ALTERED ELECTRICAL CHARACTERISTICS EXAMPLES

Figure 6.14 Curve tracer results showing forward conduction characteristics of a good silicon diode.

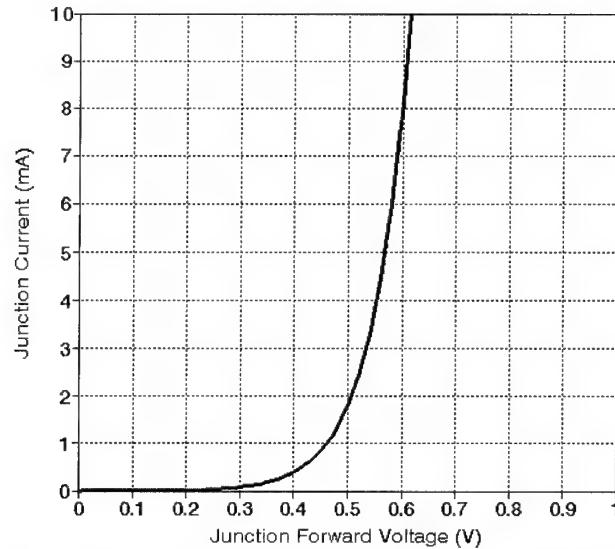
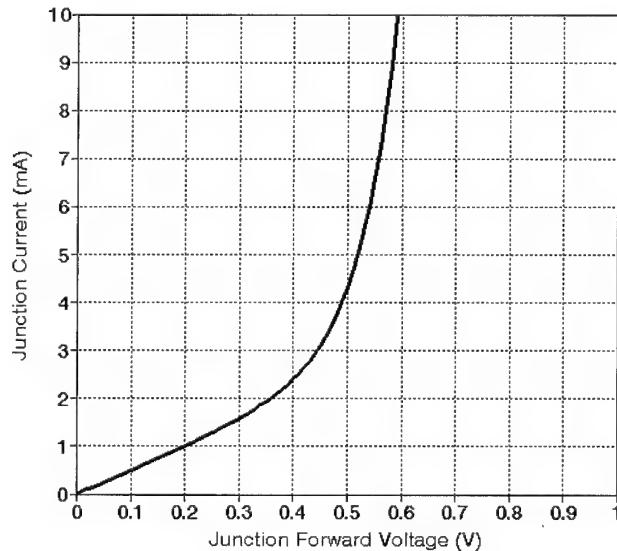


Figure 6.15 Curve tracer results showing forward conduction characteristics of a silicon diode with excessive forward leakage current.



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SECTION C

FAILURE ANALYSIS PROCEDURES

OVERVIEW

Introduction The complexity of microelectronic devices and their many failure mechanisms makes it difficult to use a consistent step-by-step procedure for failure analysis. The sheer number of different procedures is beyond the scope of this handbook and has been covered elsewhere [6.1]. Nonetheless, some of the more common techniques are covered in this section.

Examination Guidelines Field and laboratory examination of microelectronic devices is covered in the first two articles of this section.

Field examination of microelectronic devices is quite limited, because of the physical size of the components. Assemblies and equipment containing microelectronic devices are usually removed from the site before examination. Guidelines for removing equipment from the site and a device/equipment identification checklist is included.

General steps for the laboratory examination procedure are covered in outline form.

Analysis Procedures Laboratory analysis procedures are covered in the remaining subsections. Photographs and examples are included.

Contents Examination Guidelines

- Field Examination
- Laboratory Examination

Laboratory Procedures

- Delidding
- Decapsulation
- Passivation Removal
- Optical Microscopy
- SEM Voltage Contrast
- SEM Electron Beam Induced Current (EBIC)
- Non-Volatile Memories
- Other Techniques

FIELD EXAMINATION

Introduction Field examination of microelectronic devices is limited to what the investigator can see. A hand-held magnifying glass or low-power portable microscope is the best tool for this examination. In most cases microelectronic devices will be of interest by suspicion, rather than direct observation of their appearance.

The main reasons microelectronic devices may be of interest during field examination are:

- They have an unusual appearance, suggesting thermal or electrical failure.
- The equipment in which the devices are located may have malfunctioned.
- Identifying the devices may reveal the identity of certain pieces of badly damaged equipment. This could provide clues relative to the causes and conditions leading to the break-up and impact.
- The equipment may contain non-volatile memory devices which may have recorded data during the mishap.

Documentation Recording the model number, package type, and location of the device is essential. Hand sketches and photographic records are recommended. A list of suggested information to obtain for each device or piece of equipment is presented in Table 6.8.

Microelectronic devices will usually be located in equipment or on printed wiring boards. In this case, photograph and record any identifying information found on the equipment or printed wiring boards.

Removal Whenever possible, the equipment containing the microelectronic devices should be removed from the mishap in its entirety.

If the equipment can be removed from the aircraft, all connectors should be capped or otherwise protected prior to shipment. Loose circuit boards should be wrapped in anti-static bags. Conductive wrapping should not be used as a substitute.

Everything possible should be done to protect the equipment from x-rays, static electricity, or the accidental application of power.

Continued on next page

FIELD EXAMINATION, Continued

Table 6.8 Sample Microelectronic Device Identification Form.

Aircraft	<i>F111</i>
Sample ID#	<i>ME 101</i>
Date of Mishap	<i>04/03/90</i>
Date Removed from Site	<i>04/03/90</i>
Device Type	<i>Power Transistor</i>
Package	<i>TO-3</i>
Manufacturer's Name	<i>Motorola</i>
Manufacturer's Part Number	<i>2N5684</i>
Date Code	<i>7934</i>
Location Found At Site	<i>Separated from A/C on left side</i>
Mounting Arrangement	<i>On Aluminum Panel</i>
Equipment Function	<i>TFR Power Amplifier</i>
Comments	<i>Transistor Cases Arced Open</i>

LABORATORY EXAMINATION

The general steps to be carried out in examining microelectronic devices are outlined below.

1. Verify that all nameplate data has been recorded. Include the manufacturer, model, date code, rating, and MS number.
2. Perform a careful visual examination. Look for signs of corrosion, overheating, arcing, and mechanical damage.
3. Perform in-circuit testing, if applicable.
4. Remove the device from assembly or printed wiring board for further examination or testing.
5. Perform more detailed visual examination and functional electrical testing.
6. Examine the device by optical microscopy or SEM. Look for cracks in package, lead corrosion, discoloration or gross contamination.
7. Perform decapsulation and/or delidding, as needed, to support further examination.
8. Perform optical microscopy or SEM. Look for any visible mechanical damage, wire bonds problems, die flaws or cracks, melted areas of die, discoloration, and gross contamination.
9. Remove passivation layer from die to allow further analysis.
10. Perform SEM/EDS to verify contaminants and other identified problems.
11. Perform voltage contrast and/or EBIC to identify the source of electrical malfunctions.

DELIDDING

Overview Delidding is the procedure used to remove the lid or cover from a microelectronic device. There are several basic procedures used for delidding. These are:

- grinding
- cutting
- desoldering

In most cases combination of these methods are used for optimum results.

Metal Can The preferred method for metal can ICs and power transistors is outlined below:

1. Use a small grinding tool to reduce the thickness of the cover in an area around the perimeter of the package. Packages with round covers may be mounted in a lathe and turned down using a small file, coping saw, or conventional metal-turning tools.
2. Blow off the device to remove any metal particles from the grinding operation. This should be done, of course, before the case is perforated.
3. Peal off the lid with a needle-nose pliers or tweezers.

Ceramic IC In this method a machine vise is modified by adding knife blades to the top surface of each jaw. The cutting edges of the knife blades face each other. The procedure below opens the ceramic package, either by penetrating the glass seal at the lead frame interface, or by removing soldered lids on the top surface of the package.

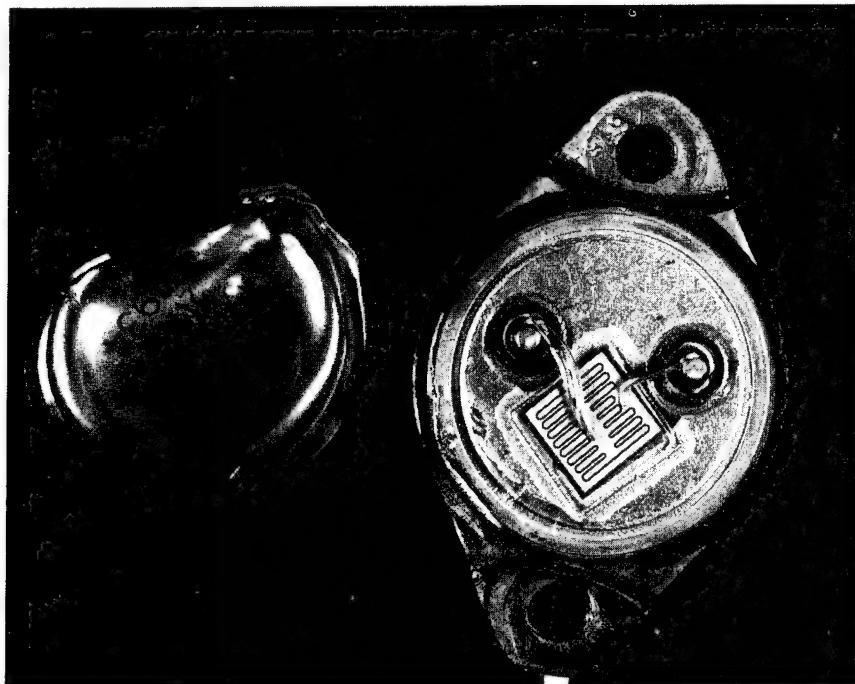
1. Place the device in the modified vice with the knife edges contacting the seal. Use just enough pressure to hold the device in place.
2. Heat the lid for about five seconds with a small butane-oxygen blow torch.
3. Remove the heat and slowly close the vise to increase the pressure.
4. Repeat steps 2 and 3 until the lid is sheared off at the seal.

Precaution Wire bonds inside microelectronic devices are extremely fragile. Practice on sample devices before attempting to open devices obtained from a mishap.

Continued on next page

DELIDDING EXAMPLES

Figure 6.16 Figure 6.16 shows a TO-3 package power transistor which has been opened by mounting in a lathe and thinning the lid near the bottom. Magnification: about 2X.



DECAPSULATION

Overview Decapsulation is the procedure used to remove the molding material from plastic packaged ICs and transistors.

There are three basic methods for decapsulation. These are:

- mechanical abrasion and cutting
- chemical etching
- plasma etching

Each method has its advantages for specific types of devices.

Mechanical Abrasion The plastic is removed by grinding or sandblasting. Mechanical abrasion is simple, but appropriate only for larger devices. In addition, it generates dirt and dust which can contaminate the device.

Chemical Etching In this process the plastic molding material is dissolved with specialized solvents and acids. Chemical etching is difficult to control, but works on a broad range of encapsulated devices. It can leave chemical residues which interfere with the analysis. Information on etchants and the specific chemical reactions can be found in [6.1] and [6.12] respectively.

Plasma Etching A radio frequency (RF) energy source is used to ionize gas in a reaction chamber. The IC is placed in a chamber and the ionized gas attacks the plastic and IC layer materials. Plasma etchers are extremely controllable and do not leave chemical by-products behind as in chemical etching. Plasma etching is covered in [6.13] and [6.14].

Preparation Although it is possible to etch devices with little preparation, better results are obtained when the package is mechanically abraded. Usually the package is ground down or milled to thin the molding material in the area above the die. This leaves less material to be removed by chemical action and allows the reactions to be controlled better. Since the unground part of the package will remain partially intact, it helps hold the device together after etching.

Continued on next page

DECAPSULATION, Continued

Etchants The two most common reagents are concentrated nitric and concentrated sulfuric acid. Many of the etching procedures in the literature use fuming nitric and fuming sulfuric acid. These acids are not merely concentrated versions of the same chemical. They actually have a different chemical makeup which makes them extremely dangerous, but particularly well suited for dissolving plastics. The fuming versions of these acids are powerful oxidizers and have many unstable and explosive reactions with other common laboratory agents.

Several commercially available organic solvents are formulated specifically for dissolving encapsulants. Two sources for these solvents are:

1. Dynaloy, Inc.
Hanover, New Jersey.
2. Emerson and Cuming, Inc.
Woburn, Massachusetts.

Table 6.9 lists a variety of solvents suitable for electronic applications. They are available from Dynaloy, Inc.

Precaution Decapsulation involves the use of some of the most dangerous and poisonous chemical agents known. Anyone attempting decapsulation activities should be trained in the use of these chemicals and should take proper safety precautions. Proper protective clothing, handling and disposal procedures must be used. Review their material safety data sheets (MSDSs) and consult with safety personnel before attempting to use the materials.

The waste products from decapsulation are considered hazardous materials. They must be disposed of in accordance with the legal disposal requirements for hazardous materials at your facility.

Procedure The procedure depends on the material being dissolved and the solvent. Several detailed procedures are presented in [6.1] and [6.12].

The procedure for concentrated sulfuric acid is outlined below [6.1]:

1. Mill a small well in the plastic above the die
2. Boil the acid in a small beaker. The concentrated acid should be boiled down to one-half its original volume to remove as much water as possible.
3. Bake the device at 200°C (392°F) for 30 minutes to remove moisture.

Continued on next page

DECAPSULATION, Continued

Procedure (Cont'd)

4. Immerse the device in the acid until the die becomes visible. It will be necessary to remove the device from the acid to inspect it as the acid becomes dark once some of the plastic has been dissolved.
5. Rinse in deionized water to remove the acid.
6. Rinse in methanol and dry gently in air.

Table 6.9

SOLVENT	ELECTRONIC					
	MATERIAL TYPE					
	Acrylics (cured)	Epoxies (cured)	Urethanes (cured)	Silicones (cured)	Polyesters	Conformal Coatings
						Positive Photoresists
SOLVENT SELECTION GUIDE						
METHANOL BASE						
URESOLVE BLUE		E1,E2, E3,E4			E1	
DYNASOLVE 190		E1,E2, E3,E4	E1,E4		E1	
URESOLVE 411		E1,E2, E3,E4	E1,E4		E1	
PROPYLENE GLYCOL ETHER BASE						
DYNASOLVE 700		E4,E6				
DYNASOLVE 710	E4,E6, E8	E4,E6, E8,E9	E4,E6			
DYNASOLVE 711	E4,E6, E8	E4,E6, E8,E9	E4,E6		E9, E10	
DYNASOLVE 750	E4,E6, E8	E4,E6, E8,E9	E4,E6			
ETHYLENE GLYCOL ETHER BASE						
URESOLVE HF		E4,E6				
URESOLVE PLUS	E4,E6, E8	E4,E6, E8,E9	E4,E6			
URESOLVE PLUS SG	E4,E6, E8	E4,E6, E8,E9	E4,E6		E9, E10	
URESOLVE PLUS 500	E4,E6, E8	E4,E6, E8,E9	E4,E6			
DYNASOLVE 611					E9, E10	
METHYLENE CHLORIDE BASE						
DYNASOLVE 165	E1,E4, E5,E6			E1		
DYNASOLVE 210		E1,E4, E6,E7		E1		
N-METHYL PYRROLIDONE BASE						
NMP	E4,E5, E6,E8				E9, E10	
DYNASOLVE 180	E4,E5, E6,E8				E9, E10	
DYNASOLVE 185	E4,E5, E6,E8				E9, E10	
DYNASOLVE 185 SG	E4,E5, E6,E8				E9, E10	
HYDROCARBON BASE						
DYNASOLVE 220		E1,E4, E6,E7		E1		
DYNASOLVE 225		E1,E4, E6,E7		E1		
DYNASOLVE 230		E1,E4, E6,E7		E1		
SPECIAL SOLVENTS						
DECAP	E4,E5, E6					
DYNASOLVE 100	E4,E6	E4,E6	E4,E6			
DYNASOLVE 150				E1	E1	
DYNASOLVE 699	E1,E4	E1			E1	

SOLVENT APPLICATIONS

ELECTRONIC	
E1	Conformal Coating Removal
E2	Cable Assembly Repair
E3	Electrical Connector Repair
E4	Depotting
E5	Deflashing
E6	Decapsulation
E7	Removal of RTV's from CRT Tubes
E8	Deinking
E9	Surface Preparation
E10	Photo Resist Stripping

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PASSIVATION REMOVAL

Application Most SEM examination techniques require that the passivation layer be removed from the device surface.

Procedure Glass passivation can be removed by wet chemical etching [6.15].

Etch Evaluation The glass removal rate should be evaluated using a trial exposure of 30 seconds. After each exposure wash in deionized water for 30-60 seconds, rinse in isopropyl alcohol, and dry gently with dry nitrogen.

Observe the progress of the etching with an optical microscope. The die is examined for the appearance of a vivid color that is characteristic of the thermal oxide. If the colors are pastel shades or non-existent, additional etching is needed. Exposed aluminum at the bond pads and conductors should be checked for damage or undercutting.

The device should undergo a functional test following each exposure. Power supply currents are a good indicator that device characteristics have not been altered. No further etching should be attempted if supply currents increase. Proper etching may be verified by observing the behavior of the IC with the SEM voltage contrast method. Observe dc voltage contrast imaging for metal conductors and ac voltage contrast imaging for diffused areas. SEM operating parameters can also be evaluated at this time.

The etch evaluation process should determine the following parameters:

- appropriate etchant formulation
- etch time
- optical appearance when properly etched
- SEM operating parameters

Etchants There are two etchants reported in [6.15]. These are:

Etchant Number 1

125 ml 48% HF
25 ml 70% HNO₃
250 ml glycerine

Etchant Number 2

280 ml 40% NH₄F
35 ml 48% HF

Etchant number 1 works well for bipolar devices while etchant number 2 works well for all devices.

Continued on next page

PASSIVATION REMOVAL, Continued

Precautions Etchants should be evaluated on sample ICs before use, due to the wide variation of etch rates on different types of ICs.

Glass characteristics can vary from lot to lot from the same manufacturer. This makes it difficult to develop consistent etch exposure times.

Etchants that are too aggressive will produce grooves adjacent to the metal conductors. They will also etch the aluminum and cause deterioration of device performance.

OPTICAL MICROSCOPY

Introduction The primary advantages of an optical microscope are the minimum sample preparation required and the ability to inspect without damage or modification to the device. The observation and photographic recording of color is another distinct advantage. This technique may be used to identify manufacturing defects, mechanical damage, thermal damage, and corrosion.

Metallurgical microscopes are usually used for failure analysis examination of microelectronic devices because of their high quality optics, and the number of illumination options available. An excellent reference on optical microscopy is [6.16]. Additional examples of optical microscopy applied to microelectronic devices can be found in [6.3].

Bright Field In bright field illumination the image is formed by reflected light. The light source is internal to the microscope optics and is directed through the objective stage perpendicular to the surface of the sample. The light reflects off the surface of the sample and re-enters the objective lens. Since most of the light that reflects off the sample is directed back through the optics; the illumination is very strong and accentuates reflective properties of the sample.

Dark Field In dark field illumination the image is formed by light which is reflected off the sample at an oblique angle. Image contrast is generally greater than with brightfield. For this reason, it is often possible to see features not visible with bright field.

OPTICAL MICROSCOPY EXAMPLES

Figure 6.17 Figure 6.17 shows an IC examined using bright field illumination. Magnification: about 150X.

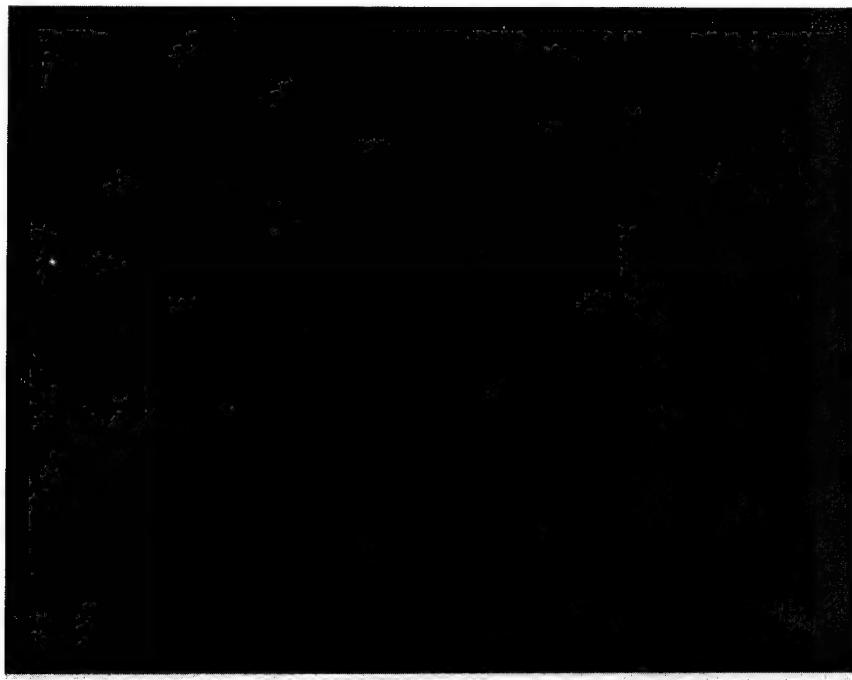
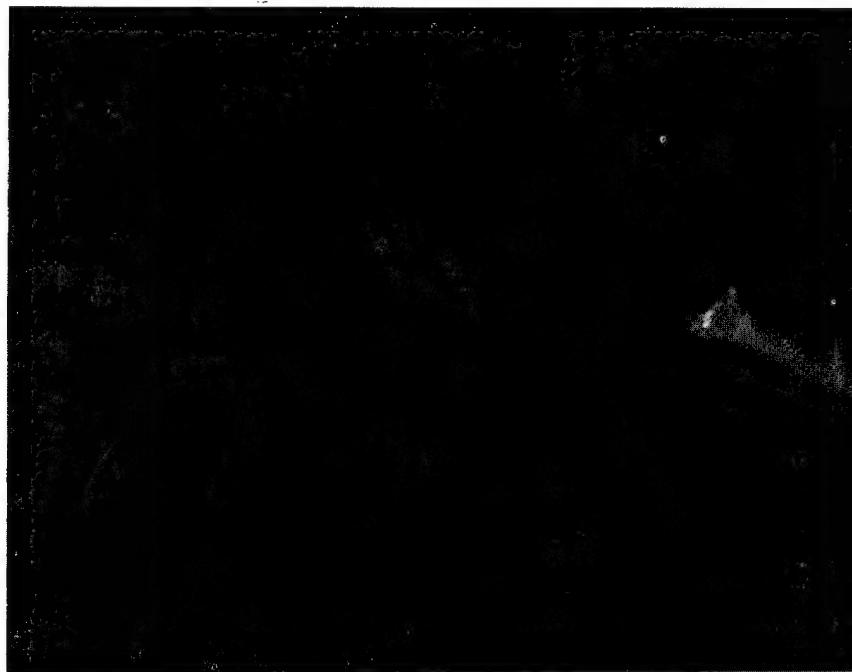


Figure 6.18 Figure 6.18 shows an IC examined using dark field illumination. Magnification: about 150X.



SEM VOLTAGE CONTRAST

Mechanism In voltage contrast imaging an IC is examined and electrically operated while in the SEM vacuum chamber. Special connectors are used to connect external electrical circuits to the IC through the wall of the vacuum chamber.

Secondary electron emission is affected by the voltage applied to the surface that the beam is striking. Positive potentials appear darker, while negative potentials appear brighter than those at ground potential.

The effect works well over the range of voltages used for IC operation. The voltage changes that occur in 5 Volt logic circuits can easily be distinguished.

Preparation The IC must be delidded or decapsulated so that the die can be imaged with the SEM. The electrical connections must be intact to operate the device.

The passivation layer must be removed to allow the electron beam to contact the metallization layer.

The device must be fitted with interconnections for the leads which allow the device to be modulated by external circuits. The device should not be connected to the SEM ground, as with most other samples. The appropriate leads should be brought out through the interconnection system, so that grounding can be done externally. This provides additional flexibility in imaging.

Precautions It is possible to damage the IC if the beam sweep area is too small, or if the beam current becomes too high. Sensitivity to beam current depends on the particular IC technology, feature size, and other factors. Preliminary testing on samples should be conducted to verify the acceptable levels.

Application The technique works well for the identification of cracks, metallization problems, and other failures where circuit connections are affected. When the IC is statically activated, the metallization traces will appear darker or lighter, depending on their voltage levels.

In dynamic applications, such as counters and memory circuits, the circuit is clocked. One or more frequencies may be present on the traces. If the voltages change during the beam scanning period, the traces will take on a striped appearance. This is sometimes called stroboscopic voltage contrast.

SEM VOLTAGE CONTRAST, Continued

Application (Cont'd) The striping effect obtained with this technique depends on the orientation of the trace with respect to the beam scanning direction and to the frequency of the modulation voltage. Circuit frequencies usually can be chosen to provide a useful spacing of the stripes. For example, if the frame rate is 60 Hz and 30 stripes on a particular trace are desired, then the frequency on that trace should be 30x60, or 1800 Hz.

If stroboscopic voltage contrast photographs are taken on an SEM with a long photo sweep rate, the circuit frequency must be reduced accordingly.

Examples Stroboscopic voltage contrast is illustrated in Figure 6.19, which shows an operating memory IC. The different stripe widths on the right side of the photo illustrate the various frequencies of the address lines used to activate the circuit.

Figure 6.20 shows a broken interconnect line. The break becomes very obvious, because the two sides of the connection are at different voltages.

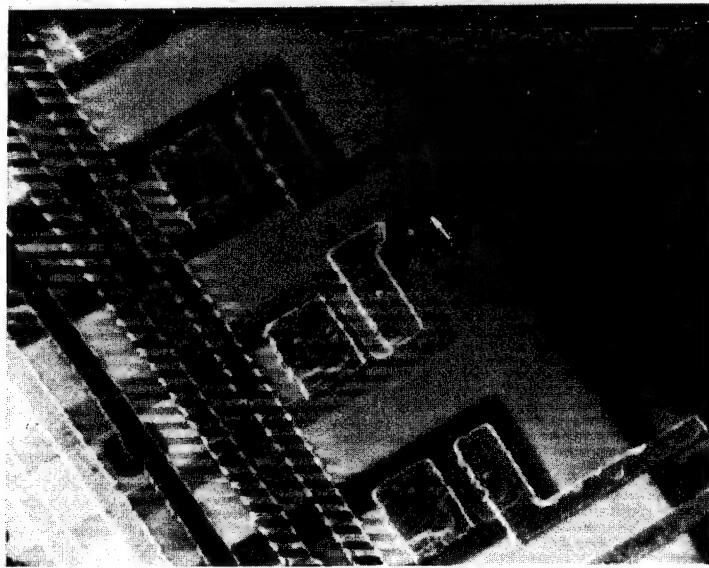
Photos courtesy of Martin Marietta Corporation.

SEM VOLTAGE CONTRAST EXAMPLES

Figure 6.19 Stroboscopic voltages contrast of a memory IC shows different frequencies of operation. Magnification: about 500X.



Figure 6.20 Broken interconnect made visible by the voltage difference across break. See arrow in center of photograph. Magnification: about 1000X.



ELECTRON BEAM INDUCED CURRENT

Mechanism Electron beam induced current (EBIC) is an SEM imaging technique in which the electron beam alters the conducting characteristics of P-N junctions in the device being examined. The measurement is usually made on a reverse-based junction, although this is not always necessary to obtain a good image. When the electron beam strikes the junction, the junction develops a voltage. The voltage is amplified by an external amplifier and the resulting signal is used to modulate the SEM image intensity.

Beam voltage determines the penetration into the material, and is used to gauge junction depth.

One side of the junction is usually connected to ground, either directly or through a power supply which biases the conducting state of the junction. This connection allows beam current to return to the SEM electrical ground.

In P-N junctions, the anode is positively-doped silicon and will assume a negative voltage (relative to the cathode) when the electron beam strikes the junction. That is, it is as if the beam causes a reverse bias of the junction. If external bias is applied, it is also in the reverse direction.

A detailed discussion and several good examples can be found in [6.3].

Preparation The device must be delidded or decapsulated.

In some cases, the device junction is reverse-biased with an external power supply.

Application The junction usually appears as a bright area in the EBIC image.

Penetration Depth for Various Beam Voltages

Material	Depth in Microns		
	5 kV	10 kV	15 kV
Silicon	0.4	1.2	2.3
Aluminum	0.3	1.0	2.0
Gold	0.1	0.3	0.5

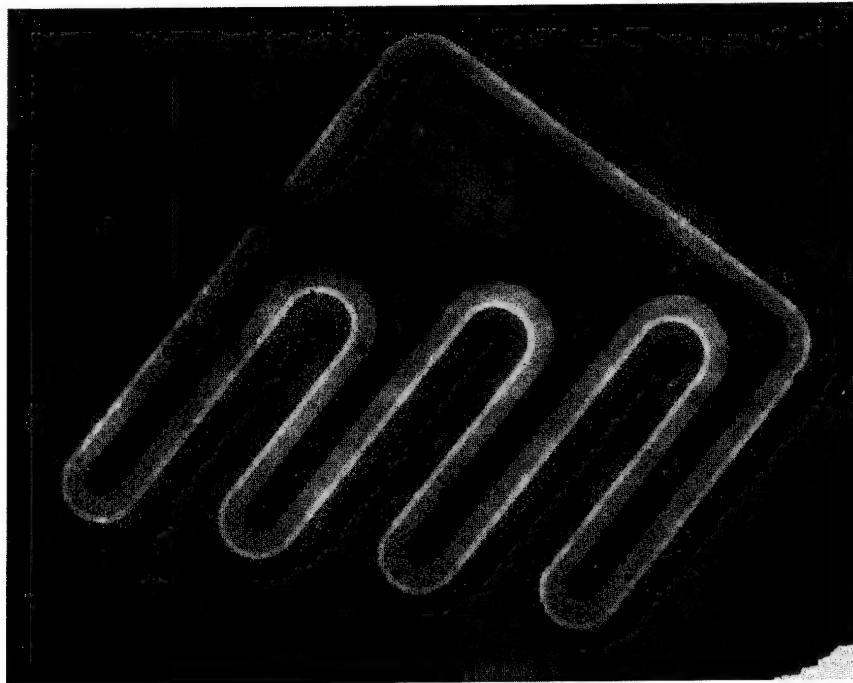
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ELECTRON BEAM INDUCED CURRENT, Continued

Precautions It is possible to damage the IC if the beam sweep area is too small, or if the beam current becomes too high. Sensitivity to beam current depends on the particular IC technology, feature size, and other factors. Preliminary testing on samples should be conducted to verify the acceptable levels.

Examples Secondary emission and EBIC signals are combined to form the image shown in Figure 6.21. The photo shows an NPN transistor examined at 12 kV.

Figure 6.21 EBIC photo of NPN transistor junction. Magnification about 20X.



NON-VOLATILE MEMORY

Overview Non-volatile memory (NVM) devices in aircraft record and retain data which can be useful during mishap investigation. NVM retains data when power is removed, and thus may provide data hours, or even days, after the actual mishap. NVM is used to record various types of information, including:

- pilot inputs for flight parameters
- operating data recorded for equipment maintenance
- digital flight data recorders for maintenance and safety monitoring

Types of NVM There are many types of NVM devices used in electronic equipment. Only some of these devices are suitable for applications where the contents will be altered in operation.

Conventional EPROM (Electrically Programmable Read Only Memory) devices, which are programmed at low speed and/or high voltage, are not useful for storing data while the aircraft is operating. They may contain useful information, but are not as critical to the investigation.

There are two types of NVM devices applicable to mishap investigation. They are:

1. EAROM - Electrically Alterable Read Only Memory. These can be reprogrammed with normal circuit voltages but retain their contents when power is removed.
2. Battery backed RAM. Random Access Memory devices are connected to a battery supported power supply. They can be reprogrammed in circuit. When power is removed they are energized at low voltage, with a battery back-up power circuit. The contents are retained as long as the battery can supply power.

Field Handling Whenever possible, the equipment containing the NVM should be removed from the mishap in its entirety. This maximizes the chances of retrieving all the information, since the supporting hardware and software may be used at the depot to exercise the NVM devices.

Everything possible should be done to protect the equipment from X-rays, static electricity, or the accidental application of power.

If the equipment can be removed from the aircraft, all connectors should be capped, or otherwise protected, prior to shipment. Loose printed wiring boards should be wrapped in anti-static bags. Conductive wrapping should not be used, as inadvertent short circuiting of back-up batteries could occur.

Continued on next page

NON-VOLATILE MEMORY, Continued

Laboratory Examination The retrieval of data from NVM must be treated in stages, depending on the condition of the equipment and the type and application of NVM devices. A brief outline of the approach is as follows:

1. Equipment containing NVM should be energized by personnel familiar with the equipment. Special test equipment may be needed to energize the equipment, while avoiding any potential self-test activities which could damage the memory contents.
2. Printed wiring boards should not be removed from equipment until all power sources have been identified. This is necessary to avoid separation of the NVM devices from back-up battery supplies.
3. Individual devices of the true NVM (not battery back-up) type can sometimes be read using the specialized programming units which also contain readout capability.
4. If the package of an NVM device is damaged, but the die is essentially intact, the device may be read by probing the bond pads. This will require device decapsulation, and represents a serious risk to the device.
5. When significant damage to the die has occurred, it may be possible to probe the device metallization to read out some of the memory cells. This requires decapsulation and removal of the passivation layer and, therefore, is not reliable.

Precaution

NVM memory devices are extremely sensitive to electrostatic discharge, ultraviolet, and x-ray radiation.

Memory cells in most EEPROM devices function with stored charges buried in the device structure. The charge and, therefore, memory contents can be altered by radiation or electrical probing. Previous experience, coupled with extreme caution, must be used when attempting to retrieve data from these devices.

OTHER TECHNIQUES

Hermeticity Techniques In general, failure analysis techniques for package leaks will include a visual examination to localize the leakage site, early non-destructive examination by light microscope or SEM, device dismantling or cross-sectioning, and then metallurgical analysis.

Test methods and acceptance limits for microelectronic packages are included in [6.8]. Method 1014 includes test methods using:

- helium and radioisotope tracer gases
- fluorocarbon bubbles
- dye penetrants
- package weight gain tests.

Package Ambient Gas Analysis This test analyzes the composition of the gas inside a hermetically sealed container. Gas volumes inside integrated circuit devices are on the order of 0.01 to 0.85 cc and highly specialized equipment is required to perform the analysis. Microelectronic packages are usually back-filled with dry nitrogen, at or near atmospheric pressure, before being hermetically sealed. Contaminants in the nitrogen are detected using mass spectrometry.

Thermal Mapping Techniques These techniques analyze temperature patterns in operating semiconductor devices and integrated circuits. Their applications are limited to operating equipment and may not be suitable for accident investigation because of damage to the circuitry. The basic method involves the use of infrared (IR) scanning equipment.

Liquid Crystal Analysis Techniques Liquid crystal films create polarization and intensity changes on a microscopic level when applied directly to the surface of a microelectronic device.

Liquid crystals can be used in the following ways:

1. For locating areas of high power dissipation in microelectronic devices by causing color changes which indicate temperature gradients.
2. By magnifying the effects of sub-micron oxide defects so that they can be observed optically.
3. For displaying active areas of an operating device and detecting logic circuit failures.

Continued on next page

OTHER TECHNIQUES, Continued

Scanning Acoustical Microscopy In the Scanning Acoustic Microscope (SAM) an acoustic wave is transmitted through the device and the transmission characteristics are used to generate a map of the device features. SAM is especially useful in detecting cracks, flaws, and mounting anomalies inside packaged microelectronic devices.

Scanning Laser Acoustic Microscope In the Scanning Laser Acoustic Microscope (SLAM), the sample is subjected to a plane acoustic wave and illuminated with laser light. The sound is scattered and absorbed within the sample, according to the internal elastic microstructure of the material. The principle of imaging is based on the minute displacements which occur as the sound wave propagates in the sample. Useful information is morphological in nature. The technique can be used to sort and classify materials, detect and localize flaws, identify defects in optically opaque samples, and map compressibility and density variations on a microscopic scale.

Particle Impact Noise Detection Particle Impact Noise Detection (PIND) tests are used to identify loose particles inside a device cavity. One procedure is described in MIL Standard 883B, and is identified as method 2020.1. The apparatus consists of a transducer and vibrator assembly, which is used to mechanically excite the device under test and detect the presence of vibrations caused by particles inside the device package.

Mechanical Testing Wire bond tests are used to determine the mechanical strength of wire bonds. The wires may be bonded to the die, to the lead frame, or to a ceramic substrate. Several tests have been devised. In each, a force is applied to the bond until failure occurs. Two common tests are described below. Failure criteria are given in [6.8] and [6.1].

1. In the **bond pull** test, the wire is pulled in a direction perpendicular to the die. This test can be done on one bond by cutting the wire, or on both bonds simultaneously when the wire is not cut.
2. The **bond peel** test is usually applied to external leads, such as circuit board or hybrid IC leads. A peeling stress is applied to induce the failure.

Die attach tests verify the integrity of the die attachment to the package or hybrid substrate. This is done by applying a shear force and measuring the force at which failure occurs.

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Glossary of Terms

Alloy

A combination of elements that results in a substance possessing metallic properties.

Annealing

A heating and cooling operation which is performed on a metal after it has been worked. Annealing is used to improve ductility, relieve internal stress, and refine the grain structure.

Anode

An electrode or terminal through which currents enters a metallic conductor or electrical device. Usually a positive terminal.

Arc

A discharge of electricity through a gas, normally characterized by a voltage drop in the immediate vicinity of the cathode approximately equal to the ionization potential of the gas.

Arc tracking

A mechanism that occurs on insulating materials in which electrical discharges break down the chemical structure of the material, leaving behind more conductive materials which tend to degrade the materials insulating properties.

Arc tracking resistance

The ability of an insulating material to withstand electrical discharges without degradation of its insulating properties.

Bimetallic Element

An actuating element consisting of two strips of metal with different coefficients of thermal expansion bound together in such a way that the internal strains caused by temperature changes bend the compound strip.

Backscattered Electrons (BSE)

Electrons arising from the elastic collision between the electrons produced by the electron gun of the scanning electron microscope and the nuclei of the specimen. The BSE yield is strongly dependent on atomic number.

Backscatter (BSE) Image

An image based on backscattered electrons ((BSE). The BSE image reveals both compositional and topographic information about the specimen. The intensity of a BSE image increases with increasing atomic number.

Bent

A deviation from the original line or plane usually caused by a lateral force.

Capacitor

An electric circuit component or device in which voltage developed across the device results in the storage of energy in an electric field.

Cathode

An electrode or terminal through which current leaves a metallic conductor or electrical device. Usually a negative terminal.

Chafed

Frictional wear damage usually caused by two parts rubbing together with limited motion.

Chipped

A breaking away of the edge, corner, or surface usually caused by heavy impact.

Coefficient of Thermal Expansion

The ratio of increase of length, area or volume of a body per degree rise in temperature to its length, area or volume respectively, at some specified temperature, commonly 0°C.

Conductor

A substance or body that allows a current of electricity to pass continuously along it.

Contact

A conducting part that acts with another conducting part to make or break a circuit.

Conventional Current

An arbitrary convention which represents current flow from positive (anode) to negative (cathode) potentials.

Cracked

A narrow fissure or rupture caused by fracture of the material; partial separation of the material which may progress into a complete break.

Current

The flow of electric charge. Measured in Amperes.

Dendrite

A crystal that has a tree-like branching pattern.

Dielectric Withstand

The ability of insulating materials and spacings to withstand specified overvoltages for a specified time without flashover or puncture.

Dot Map

The imaging of sites of x-ray emission from a specimen. Also called an X-ray Map. An X-ray Map is produced with a scanning electron microscope.

Electrical Load

The end use equipment or apparatus supplied by an electric power supply circuit. Also used to refer to the current required by the load.

Energy-Dispersive Spectroscopy (EDS)

A method of x-ray analysis which discriminates among the energy levels of characteristic x-rays produced during electron-beam irradiation. Also called energy dispersive x-ray analysis. EDS is conducted with a scanning electron microscope.

Failure Condition

The effect or event which causes damage to a device or a component.

Flashover

The sudden catastrophic failure of a insulation system separating two energized metal parts or conductors. Flashover is usually accompanied by a visible electrical discharge.

Grain Size

For metals, a measure of the areas or volumes of grains in a polycrystalline material, usually expressed as an average when the individual sizes are fairly uniform.

Hertz

A unit of frequency. One Hertz equals one cycle per second. Abbreviated = Hz.

Inductor

An electric circuit component or device in which current flows through the device result in storage of energy in a magnetic field.

Infrared

The region of the electromagnetic spectrum between the long-wavelength extreme of the visible spectrum (about 0.7 μm) and the shortest microwaves (about 1 mm).

Insulator

A substance or body, the conductivity of which is zero or, in practice, very small.

Leakage Current

The current which flows between two energized metal parts which are separated by an insulating air space or solid insulation material.

Metallograph

An optical instrument designed for both visual observation and photomicrography of prepared surfaces of opaque materials at magnifications from about 25 to 2000.

Metallurgy

The science and technology of metals.

Microscope

An optical instrument consisting of a lens or combination of lenses for making enlarged images of minute objects.

Mishap

An unexpected event or operation of equipment, possibly involving damage to equipment or injury to personnel.

Migration

In assembled involving metal, the undesirable plating or dislocation of metal constituents. Metal migration usually results in some decrease in performance, such as increased leakage current.

Motor

A rotating machine that converts electrical energy into mechanical energy.

Multimeter

An instrument for measuring electric circuit quantities such as voltage, current, and resistance. A multimeter with a digital display is called a digital multimeter and is referred to as a DMM.

Necking

Localized reduction in cross sectional area during deformation under tensile load.

Nicked

A sharp surface indentation caused by impact of a foreign object.

Overcurrent

Any current in excess of the rated current of equipment or the ampacity of a conductor.

Pip

Small mound-like deposit on the surface of a material or object.

Pitted

Small irregular-shaped cavities in the surface of a material usually caused by corrosion, chipping, or heavy electrical discharge.

Polymer

A natural or synthetic chemical compound or mixture of compounds formed by polymerization and consisting essentially of repeating structural units.

Post-oxidized

Refers to the process of preparing sintered circuit breaker contacts made of AgCdO alloys. The contact form is prepared using Cd powder in the alloy prior to sintering. Oxidation is carried out after sintering.

Potting Compound

An insulating material used to seal components and associated conductors which provides protection against contaminants.

Pre-oxidized

Refers to the process of preparing sintered circuit breaker contacts made of AgCdO alloys. The contact form is prepared using CdO powder in the alloy prior to sintering.

Radiograph

A photograph shadow image resulting from uneven absorption of radiation in the object being examined.

Recrystallization temperature

The approximate minimum temperature at which complete recrystallization of a cold worked metal occurs within a specified time.

Resistance

The opposition of current flow in a conductor. In dc circuits it is the ratio of voltage to current.

rms

The root mean square value of an alternating voltage or current. The rms value is defined as the square root of the mean value of the square of the voltage or current values during a complete cycle.

Scanning Electron Microscope (SEM)

A type of microscope in which the object to be examined is placed in a vacuum chamber and subjected to a scanned electron beam. An image is produced on a cathode ray tube by detecting secondary electrons generated by the scanned beam. Magnifications up to 200,000 times are typical.

Sinter

To heat a mass of fine particles for a prolonged time below the melting point, usually to cause agglomeration.

Solder

A eutectic alloy of tin and lead used for electrical connection and mounting of components. Typical alloys have compositions of about 60% tin and 40% lead.

Spectrograph

An apparatus for dispersing radiation into a spectrum and for photographing or mapping the spectrum.

Thermoplastic

A plastic material which softens or fuses when heated and hardens again when cooled.

Transformer

An electric device, without continuously moving parts, which by electromagnetic induction transforms electric energy from one or more circuits to one or more other circuits at the same frequency, usually with changed values of voltage and current.

Voltage

The difference of electric potential measured between two points.

Voltage-Contrast Imaging

An SEM imaging technique in which a microelectronic device is energized while in the SEM vacuum chamber. Voltages present on the surface of the device modulate the secondary emission signal and the intensity of the image.

Wavelength-Dispersive Spectroscopy (WDS)

A method of x-ray analysis that employs a crystal spectrometer to discriminate characteristic x-ray wavelengths. WDS is conducted with a scanning electron microscope.

X-ray Map

The imaging of sites of X-ray emission from a specimen. Also called a Dot Map.
An X-ray Map is produced with a scanning electron microscope.